



**Calhoun: The NPS Institutional Archive**  
**DSpace Repository**

---

Theses and Dissertations

1. Thesis and Dissertation Collection, all items

---

1982

Investigations into the performance of a distributed routing protocol for packet switching networks.

Lengerich, Anthony W.

Monterey, California. Naval Postgraduate School

---

<http://hdl.handle.net/10945/20240>

---

This publication is a work of the U.S. Government as defined in Title 17, United States Code, Section 101. Copyright protection is not available for this work in the United States.

*Downloaded from NPS Archive: Calhoun*



Calhoun is the Naval Postgraduate School's public access digital repository for research materials and institutional publications created by the NPS community. Calhoun is named for Professor of Mathematics Guy K. Calhoun, NPS's first appointed -- and published -- scholarly author.

**Dudley Knox Library / Naval Postgraduate School**  
**411 Dyer Road / 1 University Circle**  
**Monterey, California USA 93943**

<http://www.nps.edu/library>



LIBRARY, NAVAL POSTGRADUATE SCHOOL  
MONTEREY, CA 93940







# NAVAL POSTGRADUATE SCHOOL

## Monterey, California



# THESIS

INVESTIGATIONS INTO THE PERFORMANCE OF  
A DISTRIBUTED ROUTING  
PROTOCOL FOR PACKET SWITCHING NETWORKS

by

Anthony W. Lengerich

December 1982

Thesis Advisor:

J. M. Wozencraft

Approved for public release; distribution unlimited

T207983



REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Investigations into the Performance of a Distributed Routing Protocol for Packet Switching Networks		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; December 1982
7. AUTHOR(s) Anthony W. Lengerich		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		8. CONTRACT OR GRANT NUMBER(s)
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE December 1982
		13. NUMBER OF PAGES 157
		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release, distribution unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Packet Switching Networks; Packet Radio; Routing Protocols; Dynamic Routing Protocols; Distributed Routing Protocols; Network Protocols; Protocol Simulation		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Packet switching communication networks employ routing protocols to determine the path traversed by each packet as it passes through the network. Routing protocols which are adaptive and can restructure the packet paths in response to localized network congestion are called "dynamic" routing protocols. Dynamic routing protocols seek to optimize the routing (provide the shortest path) for each packet in the network. Routing protocols which are unaffected by the addition or deletion of any subset of		



nodes are called "distributed" routing protocols. The relative performance of two distributed, dynamic routing protocols is determined using computer simulations. The protocols are implemented of four theoretical networks and tested under a range of network traffic loads.



Approved for Public Release, Distribution Unlimited.

Investigations into the Performance of a Distributed  
Routing Protocol for Packet Switching Networks

by

Anthony W. Lengerich  
Lieutenant Commander, United States Navy  
B.A., University of Colorado, 1971

Submitted in partial fulfillment of the  
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL

December 1982

---



25163  
C1

## ABSTRACT

Packet switching communication networks employ routing protocols to determine the path traversed by each packet as it passes through the network. Routing protocols which are adaptive and can restructure the packet paths in response to localized network congestion are called "dynamic" routing protocols. Dynamic routing protocols seek to optimize the routing (provide the shortest path) for each packet in the network. Routing protocols which are unaffected by the addition or deletion of any subset of nodes are called "distributed" routing protocols. The relative performance of two distributed, dynamic routing protocols is determined using computer simulations. The protocols are implemented on four theoretical networks and tested under a range of network traffic loads.



# TABLE OF CONTENTS

I.	INTRODUCTION . . . . .	11
	A. THE PACKET SWITCHING CONCEPT . . . . .	11
	B. NETWORK PROTOCOLS . . . . .	13
	C. DISTRIBUTED ROUTING PROTOCOLS . . . . .	17
II.	A NAVAL APPLICATION . . . . .	19
III.	PARAMETERS OF A PACKET SWITCHING NETWORK . . . . .	24
	A. QUANTIFYING PROTOCOL PERFORMANCE . . . . .	24
	B. NETWORK CONFIGURATIONS . . . . .	25
	C. CHANNEL VALUES . . . . .	33
IV.	TWO DISTRIBUTED ROUTING PROTOCOLS . . . . .	35
	A. THE HERITSCH ALGORITHM . . . . .	35
	B. THE DIJKSTRA ALGORITHM . . . . .	39
V.	SIMULATION OF THE PROTOCOLS . . . . .	44
	A. PROGRAMMING SCHEME . . . . .	44
	B. ARTIFICIALITIES OF THE SIMULATION PROGRAM . . . . .	47
	C. LIMITATIONS OF THE SIMULATION PROGRAM . . . . .	48
	D. GENERATION OF DATA . . . . .	49
VI.	RESULTS AND CONCLUSIONS . . . . .	51
	A. RESULTS . . . . .	51
	1. Comparison of Average Delivery Delay . . . . .	51



2.	Updating Requirements Versus Network Complexity . . . . .	57
3.	Synchronous Versus Asynchronous Updating Performance . . . . .	60
4.	Effects Of User Message Lengths . . . .	61
B.	SYNOPSIS OF RESULTS . . . . .	62
APPENDIX A	. . . . .	65
APPENDIX B	. . . . .	71
APPENDIX C	. . . . .	73
APPENDIX D	. . . . .	125
APPENDIX E	. . . . .	129
APPENDIX F	. . . . .	131
LIST OF REFERENCES	. . . . .	155
INITIAL DISTRIBUTION LIST	. . . . .	156



## LIST OF TABLES

I.	Significant Network Characteristics . . . . .	26
II.	Update Utilization Factors . . . . .	58





# LIST OF FIGURES

3.1.	The 5/10 Network. . . . .	33
4.1.	A 5/7 Network . . . . .	41
4.2.	Initial Channel Value Matrix For The Djikstra Algorithm. . . . .	42
4.3.	The Completed Best Path Matrix . . . . .	43
6.1.	Expected Average Delay Per Packet . . . . .	52
B.1.	The 5/10 Network . . . . .	71
B.2.	The 10/20 Network . . . . .	71
B.3.	The 15/30 Network . . . . .	72
B.4.	The 20/40 Network . . . . .	72
F.1.	Delay: Heritsch (synch), Network 5/10 . . . .	131
F.2.	Delay: Heritsch (synch), Network 10/20 . . . .	132
F.3.	Delay: Heritsch (synch), Network 15/30 . . . .	133
F.4.	Delay: Heritsch (synch), Network 20/40 . . . .	134
F.5.	Delay: Heritsch (synch), Network 10/20 (2 groups) . . . . .	135
F.6.	Delay: Heritsch (synch), Network 15/30 (3 groups) . . . . .	136
F.7.	Delay: Heritsch (asynch), Network 10/20 . . . .	137
F.8.	Delay: Heritsch (asynch), Network 15/30 . . . .	138
F.9.	Delay: Djikstra, Network 5/10 . . . . .	139
F.10.	Delay: Djikstra, Network 10/20 . . . . .	140
F.11.	Delay: Djikstra, Network 15/30 . . . . .	141
F.12.	Delay: Djikstra, Network 20/40 . . . . .	142
F.13.	Utilization Factor: Heritsch (synch), Network 5/10 . . . . .	143
F.14.	Utilization Factor: Heritsch (synch), Network 10/20 . . . . .	144
F.15.	Utilization Factor: Heritsch (synch), Network 15/30 . . . . .	145
F.16.	Utilization Factor: Heritsch (synch), Network 20/40 . . . . .	146



F.17.	Utilization Factor: Heritsch (synch), Network 10/20 (2 groups) . . . . .	147
F.18.	Utilization Factor: Heritsch (synch), Network 15/30 (3 groups) . . . . .	148
F.19.	Utilization Factor: Heritsch (asynch), Network 10/20 . . . . .	149
F.20.	Utilization Factor: Heritsch (asynch), Network 15/30 . . . . .	150
F.21.	Utilization Factor: Djikstra, Network 5/10 . .	151
F.22.	Utilization Factor: Djikstra, Network 10/20 .	152
F.23.	Utilization Factor: Djikstra, Network 15/30 .	153
F.24.	Utilization Factor: Djikstra, Network 20/40 .	154



## ACKNOWLEDGMENT

I wish to express my sincere thanks to Professor John M. Wozencraft for his guidance and patience during the course of this effort. I am indebted to him for both the concepts and the methods of research presented herein.

I dedicate this work to my wife, Linda, whose unselfish love and support made it all possible.



## I. INTRODUCTION

### A. THE PACKET SWITCHING CONCEPT

The purpose of any communications network is to provide paths for the transmission of information. It is desirable that the process which controls the transmission and reception of messages within the network be transparent to the user. To achieve this result it is required that the communication network impose a tolerable delay in the relay of messages between the originator and the destination. Further, the network should require a minimum number of instructions from the originator to accomplish the task. Ideally, the originator would be required to provide only the destination of the message to the network. The communications network should then be capable of transmitting messages to their destinations in as short a time as possible.

For communications networks which serve many users and have the requirement to exchange large amounts of data, the concept of "packet switching" may provide a method of operation which will satisfy both the speed of service and the transparency requirements of the user. In addition, an increased robustness of the network can be realized without





creating redundant circuitry if an appropriate routing algorithm is employed within the network.

The packet switching concept may be broadly described as the coordinated movement of specified length data streams within a communications network such that the data streams always travel the least congested (ie. quickest) route between the originator and the destination. Packet switching envisions the breakdown of a message into fixed length segments (packets) which are transmitted through the network to the destination by the "shortest path" (called the best path) which is known to exist at the time the packet is released into the network. The implementation of the packet switching concept requires that each station (node) in the network be capable of processing certain data concerning the structure of the network. This is necessary so that the correct routing can be assigned to each packet as it is released by the node into the network. This process can be implemented in the computer software which would control a node's participation in the network. It is important to recognize that the routing of different messages is not independent of each other, since (for example) sending all traffic via one particular link will



introduce congestion (queueing) delays that might be avoided by distributing the traffic over a variety of available links.

Packet switching techniques can be used to transmit both data and digitized voice signals. While the transparency of service to the data user is resolved through use of high bit rate transmission systems and storage buffers at each node, the real time requirement for intelligible voice communications may require the establishment of a dedicated circuit for each conversation. It may also be possible to establish a dedicated voice transmission circuit each time the transmitter is "keyed" rather than maintain a circuit for the duration of the conversation, or to always transmit over the same route (called a "virtual circuit") and to share the channel capacity with other messages during interstices in the conversation. In this way the amount of time a particular set of links remains dedicated to a single transmission is minimized.

## B. NETWORK PROTOCOLS

Central to the operation of any communications network is the set of instructions which directs the exchange of network information between nodes. These instructions may



be implemented in hardware or software and are referred to as Network Protocols. The information contained in messages generated by these protocols is used by the communications network to implement the routing of user message traffic within the network. Network Protocols are commonly divided into several hierarchical levels according to their particular function within the network. For instance, the International Standards Organization adopted a "Reference Model of Open System Interconnection" (ISO) which consists of seven layers of protocol. The different layers as described by Tanenbain [Ref. 1], are; physical layer, data link layer, network layer, transport layer, session layer, presentation layer and application layer. Heritsch, in Reference [2], addresses three levels of protocol which are of concern in studying Distributed Routing Protocols. Five of these layers are incorporated into the three protocol levels discussed by Heritsch. The interrelation of these levels and layers is presented in the following paragraphs. Two layers, the session layer and the application layer, are not considered since they are not present in the the test networks used in this study.



The lowest level of protocol is called the Node-to-Node protocol and consists of those instructions necessary to ascertain and verify that a usable communications path exists between any two adjacent nodes. This level is a combination of the physical layer and the data link layer of the ISO and serves to establish the physical exchange of data between nodes. In addition the Node to Node protocol specifies the "handshake" and "acknowledgement" processes which are required whenever messages transit between two neighboring nodes. (The term "neighboring nodes" implies that a direct two way communications path exists between adjacent nodes. Such a path is referred to as a "link".) If the computer software within the node is configured to monitor the transmission and receipt of Node to Node protocol messages, then the continuing function of verifying that a usable link exists can be accomplished without another form of protocol message being entered into the network.

The next level of protocol is the Network Management Protocol which corresponds directly to the network layer of the ISO and exchanges all the information necessary for the nodes to make decisions as to which route each message





originated by or relayed by the node should travel enroute to its destination. There are several different concepts of Network Management protocol. Since if the amount of Network Management traffic is large there is less residual capacity in the network for the transmission of user generated traffic, it is essential to establish an understanding of the portion of total network capacity required to implement a given Network Management Protocol. This study is concerned with developing such an understanding for the Network Management Protocol proposed by Heritsch [Ref. 2].

The final level of protocol is the User Service Protocol. This level is equivalent to the presentation layer of the ISO. As the name implies, this level is concerned with the interface between the user and the communications network. Functions accomplished by this protocol level may include the automatic breakdown of user messages into "packets", attaching accounting numbers to the messages and releasing or receiving messages into and from the network. At this level, tradeoffs made between network transparency and the required user interaction with the network are most apparent.



### C. DISTRIBUTED ROUTING PROTOCOLS

The singular feature which distinguishes a packet switching communications network from other communications networks is the repackaging of user messages into smaller fixed length "packets", each of which can be treated separately by the network. An advantage of using fixed length packets is that the network can seek to transmit packets via routes which currently have the fewest number of packets flowing through them. Since all packets are the same length a simple count of the number of packets waiting in queue for a specific link is a measure of the delivery delay a packet traveling that route would experience. The packet switching network attempts to minimize the delay time by routing packets over links which have the fewest number of packets active within them. It is desirable to use Distributed Routing Protocols in packet switching networks to decide which routes are shortest.

Distributed Routing Protocols are sets of instructions utilized by the network to determine on the basis of information exchanged with its neighbors which path each packet should take from its originating node to its destination node. Distributed Routing Protocols may be either synchronous or asynchronous in design.



Synchronous Distributed Routing Protocols cause all nodes within the network to change their routing instructions simultaneously and at periodic intervals. Asynchronous Distributed Routing Protocols permit the nodes to adopt new routing instructions independently whenever the node finds a path to the destination node which is shorter than the path it had previously been using.

This study examines the Distributed Routing Protocol proposed by Heritsch, [Ref. 2], determining its performance in both the synchronous and asynchronous forms and comparing its performance to the centralized routing protocol based upon the Dijkstra shortest distance algorithm [Ref. 3]. The protocols are examined using a computer simulation which uses several different networks and several levels of network message loading to provide an indication of protocol performance under a variety of conditions.



## II. A NAVAL APPLICATION

The concept of packet switching offers several advantages to users who require high data rate transmission capability and a robust communications network through which large volumes of message traffic must pass. In particular the requirements of the Navy Tactical Data System (NTDS) might in the future be met utilizing a packet switching network.

NTDS is a computer based tactical information display and decision system. NTDS information is exchanged between units of the fleet via a radio frequency digital communications network. (The term "fleet" is used here in its broadest sense and may include such diverse units as ships, all types of aircraft and troops ashore.) In its present form, the NTDS utilizes a centralized communications network with a net control station (master node) coordinating the exchange of information between units of the fleet. Participating fleet units (nodes) which have direct links with the originating node (ie. are within radio reception range) receive the transmitted message. Nodes which are beyond the radio transmission range must rely on retransmission of the information by a node which is





directly linked to a sending node. Nodes which retransmit messages may be thought of as sub level master nodes and their loss may deprive outlying nodes of information and direction.

In contrast, the packet switching concept offers a distributed communications network to support the information and coordination requirements of a widely dispersed fleet. By employing a Distributed Routing Protocol, a packet switching network can achieve increased network robustness by decentralizing the control of the network and seeking to optimize the routing of each message entered into the network. An NTDS participant would enter information into the communication network addressed to other NTDS participants as required. Upon entry the information would be reformatted into "packets" and transmitted along the best path to the destination nodes. Since all nodes are constantly "updating" their status and the status of their connecting links to other nodes in the network, the best path between any two nodes can be autonomously and continuously determined by each individual node using the network's Distributed Routing Protocol. The loss of nodes or degradation of links within the network



becomes known to all nodes and best paths can be reevaluated such that the network can continue to pass messages as long as possible. This feature of a packet switching network derives not from the physical addition of links between nodes but from considering of all nodes and links within the network as potential transmission paths to any other node in the network.

An important result of the packet switching concept is its ability to automatically relay messages to nodes which are beyond the radio reception range of the sending node. Since the sending node provides the destination addresses at the time of message transmission, the network can assume responsibility for delivery of the message rather than the conventional method of broadcasting a message and maintaining the receiving nodes within direct radio reception range. This capability would allow widely dispersed nodes to enjoy the information and coordination advantages of the NFDS without the burden of additional radio circuits. Additionally, the packet switching concept is adaptable to a variety of Anti-Jam (AJ) and Low Probability of Intercept (LPI) communications schemes which are under study or development by the Department of Defense.



In particular, packet switching is ideally suited for use with several spread spectrum communication schemes.

Conceptually, the most difficult problem to be overcome in the deployment of packet switching networks afloat is the mutual interference which two nodes transmitting simultaneously in the same frequency band might cause at the receiving node. This difficulty could be overcome using a "carrier sense" or a "listen before transmit" approach in the transmitter/receiver design and employing a signalling scheme which permits the receiver to "lock up" on the first signal received to the exclusion of all other signals. Conceivably, units could operate at slightly different carrier frequencies and the receivers would automatically shift their intermediate frequency sections to "lock up" on the sending unit's carrier. Mutual interference effects can also be ameliorated by use of wide-band pseudo-noise transmissions using uncorrelated keystreams.

It is with the possibility in mind, that the packet switching concept could improve the usability and survivability of NTDS, that this study was undertaken. To this end a set of generalized network configurations were developed so that several performance characteristics of the



packet switching concept could be determined. The specifics of the networks are outlined in Chapter III.





### III. PARAMETERS OF A PACKET SWITCHING NETWORK

#### A. QUANTIFYING PROTOCOL PERFORMANCE

Critical to determining the relative performance of different routing protocols operating within a packet switching network, is the determination of an expression (mathematical or otherwise) which provides an unbiased and meaningful basis for comparison. In this study the average delay time in delivering a packet ( $T_p$ ) is used as one measurement of protocol performance. Another measure of performance used is the utilization factor of the network ( $\rho$ ). A mathematical derivation of the inter-relation of these terms, based upon queueing theory, is presented in Appendix A.

The average time delay per packet, ( $T_p$ ) has the advantage of relating network congestion to network loading in terms of delay time, which is ultimately the most meaningful statistic to the network users. The utilization factor provides a measure of the fraction of the capacity of the network which is required to transmit user messages (packets) or network management messages (updates) given a specified network and traffic loading for the network. Both of these measures are affected by several physical



parameters of the network. For instance the processing time within a node for a packet adds delay time to the packet which is proportional only to the number of nodes traversed by the message route, hence independent of the routing protocol in use. On the other hand, if a packet must wait in a queue for an update to be transmitted on a link then the incurred delay is of interest because it represents interference by network management traffic with the transmission of user message traffic. A discussion of the various network parameters and their impact on the comparison measures, average delay per packet and update utilization factor, is presented in the next section.

## B. NETWORK CONFIGURATIONS

In order to ensure that the performance measures " $T_p$ " and " $p$ " obtained from the simulation of the network are accurate, it is necessary to determine which physical characteristics of the network effect the measures of protocol performance. By fixing these characteristics as constants for all the networks under consideration, it is possible to obtain measures of performance which are representative of the protocol's performance in networks of varying complexity and traffic loading conditions. The



network characteristics which were deemed to be significant and the values assigned to them are listed in Table I and are discussed in the paragraphs that follow.

TABLE I  
Significant Network Characteristics

<u>Parameter</u>	<u>Value</u>
packet transmission time for any link	0.05 sec.
packet processing time in any node	0.0001 sec.
update transmission time for any node	0.02 sec.
update processing time in any node	0.00001 sec.
update cycle time	0.2 sec.
update channel value calculation window	0.5 sec.
number of nodes in the network	variable
number of links in the network	variable
average number of packets per user message	variable
average number of user messages per sec.	variable
simulation run time	30 sec.

The packet transmission time is related to the length of the packet and the data transmission capacity of the link over which it is to travel. For this study only two types of messages (updates and user messages) are allowed to enter the links. User messages are subdivided into packets which are fixed in size to be 2.5 times longer than an update



message. In this way the length of an update is made to be small compared to the length of the packet. This action appears reasonable in view of the significantly smaller information content in an update versus a packet. The relative length of the the updates is also important to the performance of the distributed routing algorithm when computing channel values which are discussed in section C of this chapter. The time of 0.05 seconds selected for the transmission time of a packet, is equivalent to a packet length of 800 bits transmitted over a link with a capacity of 16,000 bits per second. Alternatively, it equates to a 120 bit packet transmitted over a link with a capacity of 2,400 bits per second.

The time required to process a packet within a node was arbitrarily chosen to be 0.0001 second and the processing time for an update was set to be one tenth of the packet processing time. This assignment also appears reasonable since in processing a packet each node must read the complete address section of each packet to determine onward routing if required and prepare a new address section for each packet which is retransmitted. On the other hand, an update message contains only a relatively small amount of





information which is either discarded or stored and relayed as required.

The update cycle time represents the frequency with which the network establishes a new best path for routing packets. An asynchronously operating protocol does not implement best paths simultaneously throughout the network but rather each node implements a new best path immediately upon determining that a new best path exists. However, if a distributed routing algorithm is implemented synchronously, it is necessary for the update message to have reached all the destinations before a new routing scheme is established in the network. An update cycle consists of two equal length time periods. During the first period nodes generate the required update messages, which receive transmission priority over packets. During the second period nodes receive and relay update messages as required. Nodes are restricted from generating update messages during the second half of the update cycle in order to allow the updates to suffuse throughout the network. If the nodes were an average of 16.4 kilometers (10 miles) apart and a maximum of 5 relays were required for each update to reach the destination node most distant from it, then the maximum time



required for an update to reach its destination can be computed as

$$\begin{aligned} \text{time required} &= \text{travel time} + \text{processing time} \\ &\quad + \text{transmission time} \end{aligned}$$

which becomes

$$t = 5 * \frac{16.4 \text{ km}}{3 * 10^8 \text{ km / sec}} + 5 * 0.00001 + 5 * 0.002$$

or

$$t = .025 \text{ sec.}$$

which is well within the available 0.1 seconds. Note that this result implies that for applications where the nodes are close (in relation to signal travel time) then the propagation time is insignificant compared to the time required to process an update through a node. By choosing an update cycle time of 0.2 second the network configurations used in the simulation could be considered representative of real world networks which have longer link lengths and/or a greater number of relays required for the delivery of an update message.

It is the complexity of the network which has the most potential for impacting on the performance of a Distributed



Routing Protocol, and it is therefore important to consider how the topology of the network interacts with the protocol. The number of nodes in a network determines the number of update messages which must be generated during each update cycle, which translates into an increasing requirement for network capacity to pass updates as the number of nodes increases. This results in less network capacity available for the transmission of user messages. The number of links in a network is also important since it determines the capacity of the network both for message and update traffic.

Traffic loading is another network parameter which may affect the performance of a Distributed Routing Protocol. For a packet switching network the traffic loading is controlled by three factors, the number of user messages entering the network per unit time and the length of the messages and the distribution of the originator and destination addresses of each message. Since messages are decomposed into fixed length packets, this last factor is the same as the number of packets in a user message.

In a real world network each of these parameters is random and it is common in queueing theory to assign a distribution to the frequency with which messages are



entered into the network and the number of packets into which a message is decomposed in terms of a probability distribution. It is often assumed that generation of messages into a network can be represented by an exponential distribution and that the number of packets in a message can be represented as a uniform distribution. Two mean values of packet distribution were used in this study (5.5 and 10.5 packets per message) so that the effects, if any, of the length of the messages on the performance of the protocols could be determined.

A final factor which may affect the performance of a Distributed Routing Protocol is the simulation run time. If the complete network is considered to be a system and the first message into the system is viewed as an impulse input into the system then it is clear that the system will undergo some period of transition between the dormant condition (ie. no inputs) and its equilibrium operating state. The length of this transition phase can be determined mathematically for the probabilistic case of a communications network only with difficulty. However, by observing the results of the network simulation after several different simulation run times it was determined





that a run time of 30 seconds allowed the transition phase to be completed and provided a period of steady state operation long enough so that meaningful data could be taken.

A total of four networks were generated for use in this study. A diagram of each network is provided in Appendix B. The number of nodes in each network varied between 5 and 20 and the number of links varied between 10 and 40. To reduce distortion of the simulation results which could be caused by different network topologies, a base network of 5 nodes and 10 links was adopted. By expanding the base network in a consistent manner, valid comparisons between the performance of a protocol and network complexity could be drawn. More complex networks were created by expanding the link/node structure of the base network. The chosen base network is illustrated in Figure 3.1 and consists of five nodes and ten links.

To provide a convenient method of referencing the networks the notation "5/10" has been adopted to denote a 5 node and 10 link network. The 5/10 network was expanded in to a 10/20 network by adding an additional 5 nodes and 10 links. Similarly, a 15/30 and 20/40 network were derived.



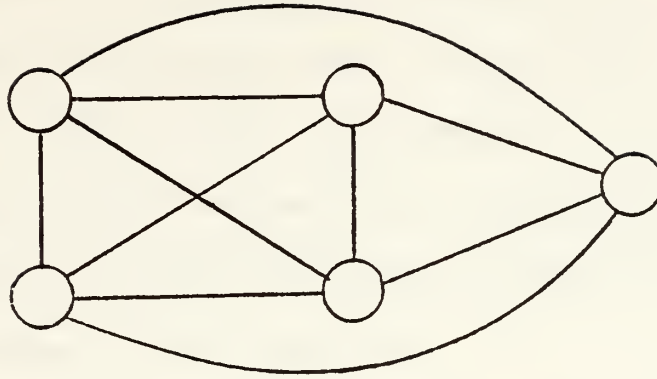


Fig. 3.1. The 5/10 Network.

Note that each succeeding network contains the preceeding network.

### C. CHANNEL VALUES

As described in section B of this chapter, the channel values ("link distances" in some literature) are computed during the update window time and represent the current demand for a particular link's services as a relay path. The channel value also represents a prediction of the demand on a particular link during the upcoming update cycle. By using these channel values it is possible to determine a path between any two nodes which will have the lowest cumulative channel value (ie. the best path during the next update cycle). It is the function of the distributed



routing protocol to generate, transmit and evaluate the channel values and establish best paths within the network. To accomplish this task the protocol generates update messages which contain channel value information. The exact content, method of relay and method of evaluating the update message is unique to each protocol.

The method of generating channel values for both the Heritsch and Djikstra algorithms as implemented in this study is identical, and a complete description can be found in Heritsch [Ref. 2]. In short, the channel value represents the average number of packets waiting in the queue to be transmitted over the link during the preceding 0.5 second of simulation time.



#### IV. TWO DISTRIBUTED ROUTING PROTOCOLS

##### A. THE HERITSCH ALGORITHM

Heritsch proposed in Reference [2], a Distributed Routing Protocol which seeks to minimize the number of update messages required to be circulated throughout a network during a single update cycle. Update messages in the Heritsch algorithm contain three items of information: the node which just relayed the update, the node which originated the update and the cumulative channel value from the node which just received the update to the node which originated the update, through the node which relayed the update. Thus each node receiving an update can compare the cumulative channel value through the relaying node to the cumulative channel value of the path over which it is currently passing packets to the node which originated the update. If the new channel value in the most recent update is less, a new best path to the node which originated the update is adopted through the node which relayed the update. In any event, the node which just received the update now generates an update message to all of its neighbor nodes (less the node which relayed the update that started it all), and informs all the neighboring nodes of the new





cummulative channel value. These nodes in turn repeat the process of evaluting the information contained in the update, establishing new best paths if the minimum cummulative channel value changes.

If no new best path is adopted and the channel value through the current best path has not changed, the node discards the update without relaying the information it contained. Since nodes which are "upstream" from the node which received the update do not change their best paths unless the best path "downstream" changes, there is no reason to relay the update further through the network. Note that even if a new best path is not adopted but the channel value changes over the current best path, this information must be relayed "upstream" since it may affect the best path decisions of "upstream" nodes. What is significant is that the algorithm purges update messages from the network at the first opportunity and thus releases channel capacity to the network for the relay of packets.

The disadvantage of the algorithm is that it does not guarantee optimum routing for each packet released into the network. It is possible for a packet to loop through several nodes before being delivered to its final



destination. This looping is the result of a packet following a best path which is changed more than once during the transit of the packet through the network.

The basic algorithm as stated above is substantially identical to the routing procedure originally used in the ARPANET. The major innovation proposed by Heritsch is that the number of update messages required in a given network could be reduced if the network was subdivided into nodal colonies which are called groups and families. A group can be defined as a collection of nodes and a family is a collection of groups. By treating the groups and families of nodes as "super nodes" it may be possible to significantly reduce the number of update messages required to implement the protocol. This reduction is accomplished by restricting the propagation of the update message to the basic group of the node which originates the update. Nodes which are connected to other groups or families originate updates which reflect the cumulative channel values from that node into the neighboring family or group. The result is that all nodes within a basic group can determine the best path to any other group or family and are not required to determine best paths to all other nodes in the network.



Thus a packet generated in one group would travel the best path to the destination group and once it reaches the destination group receive onward routing to the destination node.

The Heritsch algorithm may be implemented either synchronously or asynchronously in a packet switching network. Since the algorithm allows each node to autonomously determine new best paths it is possible to implement new best paths whenever an update is received rather than adopting best paths in synchronism with all the other nodes in the network. The only constraints to the algorithm are that update message generation be restrained to a fixed time interval so that update messages are able to reach their "final" destinations before a new update generation cycle starts.

A comparison of the algorithm's performance when implemented both synchronously and asynchronously in identical networks was accomplished as part of this study. No significant difference was found to exist in the performance of the protocol under the two implementations.

From the viewpoint of network robustness, it is desirable to implement the algorithm asynchronously.



However, for purposes of comparison with the Djikstra algorithm, (which can only be implemented synchronously), the Heritsch algorithm was restricted to the its synchronous implementation.

#### B. THE DJIKSTRA ALGORITHM

The algorithm proposed by E. Djikstra in Reference [3] is used in the current ARPANET routing protocol, which requires that each node within the network receive the channel value for each link in the network before a new best path is determined. The protocol causes each node to generate an update which contains the channel value from the originating node to each of the originating node's neighbors. The data is forwarded to each node in the network and each node enters the received channel values into a matrix which is manipulated in such a way that a best path is produced from each node to each other node in the network. The Djikstra algorithm may also be adapted to utilize the group and family scheme proposed by Heritsch. An examination of the Djikstra algorithm's performance using a group and/or family configured network was not conducted as a part of this study.





The significant differences between the two protocols are the number of update messages required to implement each protocol and the "quality" of the best path which is determined by each algorithm. The Djikstra algorithm provides an optimum quasi-static best path for each packet released into the network. That is to say, each node in turn routes the message to the next relay node along the best path in accordance with the Djikstra algorithm which is guaranteed to produce a minimum distance route. Similarly, in the Heritsch algorithm each packet is addressed to the next node along its estimated best path, but there is no guarantee that this esitimated path is indeed the optimum path. With regard to the number of update messages required by each algorithm, at first glance it would appear that the Djikstra network requires an inordinate amount of network capacity to pass updates through the network. The situation is not this bad however, since update messages which would travel along the same best path to their destination can be combined to reduce the total number of update messages required.

The matrix manipulation required by the Djikstra algorithm to determine the best paths is accomplished in the



following manner. If the 5/7 network illustrated in Figure 4.1 is considered as an example then the channel values between adjoining nodes may be represented by the symbols  $7>$  or  $<5$ , where the arrowhead indicates the direction of the channel value and the number indicates some relative measure of the channel values as they might appear at the start of any update cycle.

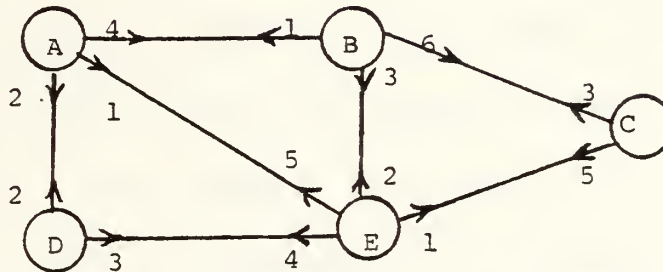


Fig. 4.1. A 5/7 Network

From this network the matrix in Figure 4.2 is constructed. Note that nodes which have no direct link between them are initially represented at the start of every cycle as having an infinite channel value between them.

Beginning with node A, observe that a direct link exists with node B and that the channel value from node A to node B



Fm \ To					
	A	B	C	D	E
A	-	4		2	1
B	1	-	6	$\infty$	3
C	$\infty$	3	-	$\infty$	5
D	2	$\infty$	$\infty$	-	3
E	5	2	1	4	-

Figure 4.2. Initial Channel Value Matrix For The Dijkstra Algorithm.

is 4 (the notation A/B/4 will be used as a convenient description of the path and its channel value). Next every other path in the network from node A to node B is considered in turn to determine if a cumulative channel value less than 4 can be found. First the A/C/ $\infty$  + C/B/3 path is considered which represents a path from node A through node C to node B. Clearly the result of this path, A/C/B/ $\infty$ , is greater than the A/B/4 path and so a new best path through node c is rejected. Next the A/D/2 + D/B/ $\infty$  = A/D/B/ $\infty$  path is considered and also rejected as a new best path. Finally, the path A/E/1 + E/B/2 = A/E/B/3 is considered and adopted as the tentative new best path from node A to node B since the resultant cumulative channel value of 3 is less than the previous value of 4.



Similarly the channel values from node B to each other node are considered and tentative best paths established. When all paths between nodes of the network are evaluated and tentative best paths established (ie. the matrix is run through completely one time) the entire process is repeated until a run through the matrix is completed with no new tentative best path adopted. When this occurs the best paths within the matrix are adopted simultaneously by all nodes of the network for the duration of the next update cycle and represent the optimum paths between nodes.

Fm \ To					
	A	B	C	D	E
A	-	3	2	2	1
B	1	-	3	3	2
C	4	3	-	6	5
D	2	5	4	-	3
E	3	2	1	4	-

Fig. 4.3. The Completed Best Path Matrix

The final result of the matrix manipulation for the update cycle considered in this example is shown in Figure 4.3.





## V. SIMULATION OF THE PROTOCOLS

### A. PROGRAMMING SCHEME

The simulation programs used in the study were written in the SIMSCRIPT II.5 programming language [Ref. 4]. This language provides an excellent vehicle for simulation work in which many events may occur almost simultaneously. In addition, the ability to control the flow of the simulation by utilizing a language generated simulation clock, provides the user with a means of obtaining data from the simulation at various times without regard for the events being processed.

Three simulation programs were developed from the program presented by Heritsch in Reference [2]. The three programs are listed at the end of this study and represent an asynchronous implementation of the Heritsch algorithm, a synchronous implementation of the Heritsch algorithm and a synchronous implementation of the Djikstra algorithm. The program listing for the synchronous implementation of the Heritsch algorithm is provided in Appendix C. Each simulation is constructed in modules which correspond to the different functions which the network and the routing protocol must perform. For example, each simulation



contains individual subroutines for the generation of updates, arrival of packets within a node and the computation of channel values. A listing of all the arrays used within the programs is provided in Appendix D to assist in tracing the functional composition of the programs. The parameters of the network under consideration are externally input into the simulation as a data set which is read by the source code during the execution of the simulation. A sample of an input data set is listed in Appendix E.

The results of the simulations can be output in several formats. The most extensive output available is a complete listing of every event occurring during the simulation. It is possible to limit the output to only the desired data by specifying the desired results in the "Special Output" subroutine of each program. The simulation programs also feature the ability to make any number of simulation runs with various input parameters during a single job submission. In addition, the results of the simulation can be diverted to either mass storage peripheral devices or the normal printer output or both. A sample of the output format used for this study is provided in Appendix E.



The implementation of the packet switching network is identical in all the simulation programs. Each link within the network is "configured" to have two input queues (a packet queue and an update queue). No queues are constructed for the input side of each node. Nodes are required to give priority to the transmission of updates over packets as would be required in a real world network. Update messages are generated only during the first half of the update cycle. The precise time at which each node generates its update message is uniformly distributed throughout the first half of the update cycle. User messages are generated into the network at time intervals which are exponentially distributed. The originating node and destination node of the message and the number of packets in the message are determined using uniformly distributed random variables. The destination node of a user message can be constrained to be outside the originating node's group and/or family in order to ensure that a specified percentage of the user messages are destined for other groups and/or families.



## B. ARTIFICIALITIES OF THE SIMULATION PROGRAM

Several artificialities were introduced into the simulation programs in order to reduce computer run time and program complexity. The most significant of these is the assumption that each node has a processor dedicated to each link entering the node. This implies that the node can simultaneously receive and process inputs on all of its links. While the capability of parallel processing is desirable in a packet switching network, it is not a requirement and may be replaced by employing a "listen-before-transmit" and "receiver-lock-up" node design, in which each node can communicate with only one other node at a time. In either case the maximum throughput of any node is considered to be determined by the output capacity of the node and not its input capacity. Thus the absence of input queues in the simulation is considered reasonable.

The simulation also does not consider the network capacity which is required to implement the Node to Node Protocol, which is vital to the operation of a packet switching network. The capacity required to carry the Node to Node protocol messages is relatively insignificant compared to that required for update and packet





transmissions. Since this study is concerned only with the performance of the routing protocol, the network capacity required by the Node to Node Protocol is disregarded.

### C. LIMITATIONS OF THE SIMULATION PROGRAM

The detailed results of the simulations depend substantially on the "seed" numbers which are used to initialize the random number streams generated internal to the SIMSCRIPT language. Since the random number streams are used to determine the origination node, destination node, time of message origination and the number of packets in a message, the simulation will provide somewhat different results for the same input parameters if different "seed" numbers are used. The variability of a particular result from the average result computed from several different runs of the simulation using the same inputs but different "seeds", was empirically determined to be on the order of 5 percent of the average result. Thus, although the graphical results of the simulations (Appendix F) appear to be discontinuous in nature as the input parameters are changed, it is expected that these perturbations are due to the "randomness" of the simulation. If a sufficient number of simulation runs were made for each data point, the average



of these points would be expected to result in a "smoother" curve.

#### D. GENERATION OF DATA

A total of twelve different simulation runs were required to produce the results presented in this study. The physical parameters of the networks and the network loadings were selected to represent the most critical and interesting aspects of the interaction between the network and the routing protocol in use. The Heritsch algorithm was synchronously implemented on four networks (5/10, 10/20, 15/30 and 20/40) and asynchronously on two networks (10/20 and 15/30). The algorithm was also synchronously implemented on the 10/20 and 15/30 networks, with the networks divided into 2 groups of 5 nodes and 3 groups of 5 nodes respectively, to investigate the capacity required to implement the algorithm in a multiple group/family network. Lastly, the Djikstra algorithm was implemented on the 5/10, 10/20, 15/30 and 20/40 networks.

The graphs of the data contained in Appendix H were derived from the data obtained from these twelve simulation runs and are presented in two forms. The first group of twelve graphs illustrates for each network and each



algorithm, the average delivery delay per packet versus the loading of the network. The second group of twelve graphs shows the packet and update utilization factors versus the network loading for each algorithm and each network. The interpretation of the data presented in the graphs is provided in Chapter VI.



## VI. RESULTS AND CONCLUSIONS

### A. RESULTS

#### 1. Comparison of Average Delivery Delay

The average delivery delay for a packet ( $T_p$ ), was computed using Equation (A-12) from Appendix A. This equation uses the measured utilization factors for updates and packets ( $p_u$  and  $p_p$ ) and a specified network loading ( $g$ ) to compute  $T_p$ . Although the equation does not provide an absolute measure of the protocol's performance it is useful in comparing the relative performance of the Djikstra algorithm to the Heritsch algorithm. Theoretically,  $T_p$  should increase dramatically as the network loading begins to approach the network capacity. Figure 6.1 illustrates the general form of the expected  $T_p$  versus  $g$  results. This expected result reflects the obvious conclusion that the delivery delay experienced by a packet must increase without bound when more packets are entering the network per second, on the average, than can be delivered by the network in a second.

From the simulation results contained in Appendix F, it is concluded that a packet switching network employing the Djikstra algorithm has less average delay per packet





than an identical network under identical loading which employs the Heritsch algorithm. Further, a network which employs the Dijkstra algorithm is capable of accepting a wider range of network loading conditions before the average delivery delay per packet increases dramatically.

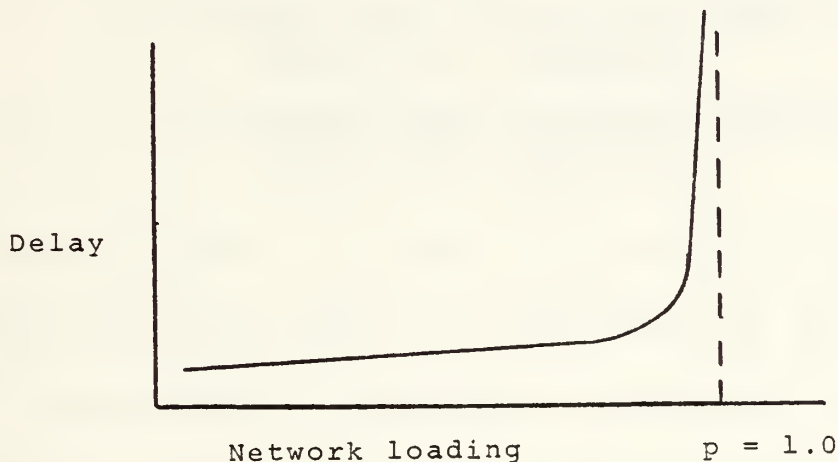


Fig. 6.1. Expected Average Delay Per Packet

The simulation results contained in the first twelve graphs of Appendix F present two measures of the average delay per packet. One curve on each graph represents the results of Equation (A-12) and the other represents the average actual delay per packet which was computed using measured data from the simulation as follows.



$$M_p = \frac{\sum t}{k} \quad (6-1)$$

where

- $M_p$  = the average delay per packet (measured)
- $\sum t$  = the sum time required to transit the network of all packets which reach their final destination
- $k$  = the total number of packets originated during the simulation which reach their final destination.

Equation (6-1) provides a much different result for the average delay per packet than does Equation (A-12), and both of these methods of predicting the protocol performance are subject to considerable inaccuracy as discussed in the following paragraphs.

As noted in Appendix A, Equation (A-12) was derived from queueing theory results which apply to networks with a fixed routing and an exponential service time distribution. Since the networks under study have a dynamic routing scheme and a fixed service time, the direct transfer of mathematical analysis from one application to the other has questionable validity. Adding to this uncertainty is the priority handling of update messages and their shorter service time, which was factored into the derivation



presented in Appendix A. Finally, some error in the results of the equation is expected due to the method of measuring the utilization factors. Since it was desirable to avoid including the transient effects of initial network start-up, the measurement of the utilization factor for each link was limited to the last half of the simulation. To accomplish this restriction, it was necessary to structure the simulation program so that any link which was busy at the instant of "half time" was identified and the fixed value of 0.05 seconds (packet transmission time) was added to the busy time of the link for the first half of the simulation. This busy time was then subtracted from the total time the link was busy throughout the simulation. The end result was a measured utilization factor for any one link which could be on the order of 0.003 percent smaller than the actual value. Despite these probable inaccuracies, the results of Equation (A-12) agree with the intuitive notion that the average delay per packet should exhibit a dramatic increase as the network loading approaches the network capacity.

In a network with fixed routing the "break point" for the rise in delay time can occur at moderate network loads if a critical subset of links is saturated ( $p = 1.0$ )



and a portion of the nodes are effectively "cut-off" from the network. The rationale for employing a dynamic routing scheme is that saturated links are bypassed (wherever possible) until their utilization factors return to a more normal level. The effect is to postpone the dramatic rise in network delay until greater network loading conditions are experienced by the network. Thus a whole cutset of the network (vice only a few links) must have a utilization factor nearly equal to unity before the characteristic delay curve exhibits its predicted rise.

The actual measurement of the average delay per packet was accomplished by accumulating the transit time of all messages which reached their destination and dividing by the number of messages which reached their destination. This measure does not include a method of determining the delay near the "break point", since near that point the number of messages which are delivered in a finite time period becomes relatively constant regardless of the network loading. Thus the result from this method of computing delay does not exhibit the strong non-linearity of Equation (A-12) in regions near utilization factors equal to unity. Most packets are not delivered under these circumstances, but





accumulate in the queues instead. If a correct expression of the average delay per packet is to be measured, it must account for the future delay which queued messages will incur as they ultimately work their way out of the network. The formulation of an expression which accurately describes the shape of the delay curve in its entirety (including the "break point") proved an elusive goal. However, it can be intuitively argued that the performance of the protocol in regions near  $p = 1.0$  must be such that the average delay per packet is increasing very dramatically as the network loading approaches close to the network capacity. This intuitive argument was verified by running the simulation for a duration of greater than 180 seconds at network loadings which produced average network utilization factors in excess of 0.996 percent. Under these conditions it was found that the average delay per packet did exhibit the expected dramatic increase. (Note that this delay was evident only after relatively long simulation run times.)

In summary, the theoretical delay curve predicted by Equation (A-12) does not accurately predict the performance of the Distributed Routing Protocol due to the adaptive nature of the protocol and the finite duration of the



measurement period. Further, a successful mathematical model for predicting the measured performance of the protocols was not found.

Lastly, the average delivery delay which resulting when the Heritsch algorithm was implemented in a test network which had the nodes divided into groups was investigated. Although the average delay per packet was significantly decreased using the group/family routing feature of the Heritsch algorithm, for the small networks studied here it was not as low as the average delay per packet experienced in a single group network of the same size which employed the Djikstra algorithm. It is believed that more significant and favorable results will be achieved if larger networks are used in comparing the performance of the Heritsch algorithm in single group versus multiple group/family networks.

## 2. Updating Requirements Versus Network Complexity

The inherent disadvantage in using Distributed Routing Protocols is the requirement to utilize a portion of the network's capacity to support the updating requirements of the protocol. Naturally, the protocol which provides the most optimum routing and requires the least network capacity



to operate is the most desirable. The amount of network capacity required by the protocol is determined by the frequency at which update messages are generated and the number of nodes by which each update must be received.

It was determined, during the course of this study that the network capacity required by each of the protocols under consideration is a nearly constant value for a given network and did not depend, to any great extent, on the traffic loading of the network. Table II contains the average update utilization factor for the Heritsch algorithm (for single and multiple group networks) and the Djikstra algorithm (for single group networks only). No data was obtained for the Heritsch network implemented on a 5/10 or 20/40 multiple group network.

TABLE II

Update Utilization Factors

Network	Heritsch (single group)	Heritsch (multiple groups)	Djikstra (single group)
5/10	.044	****	.009
10/20	.085	.028 (2)	.019
15/30	.139	.041 (3)	.023
20/40	.201	****	.028



The numbers in parenthesis in Table II indicate the number of groups into which the network under consideration was divided and the values shown are derived from a simulation using a mean of 5.5 packets per message (values obtained for a mean of 10.5 packets per message are identical). The data in Table II indicates that it is very desirable to divide a network into groups and families whenever the Heritsch algorithm is employed since the same order of routing optimization is achieved with a significant reduction in the network capacity required to support the protocol.

A significant result is that for small networks the Dijkstra algorithm requires less network capacity than does the Heritsch algorithm regardless of how the network is structured for the Heritsch algorithm. While this result may appear startling given that the Heritsch algorithm purges updates from the network which are not required to be retransmitted, it must be remembered that the Heritsch algorithm also requires all "upstream" nodes to be notified whenever a new best path is adopted or a channel value is changed. This requirement causes the generation of many additional update messages the aggregate of which is





potentially larger than the total number of update messages per cycle generated by the Dijkstra algorithm. Despite the lesser channel capacity required to implement the Dijkstra algorithm it must be remembered that the algorithm can only be implemented synchronously which may preclude its consideration in some applications. Also for large enough networks, the Dijkstra algorithm will require more channel utilization than would the Heritsch algorithm for a network which is partitioned into an appropriate hierarchy of groups and families.

### 3. Synchronous Versus Asynchronous Updating Performance

When the utilization versus network loading curves for the asynchronous implementation of the Heritsch algorithm are compared with the curves obtained for the synchronous implementation of the algorithm, it is found that there is very little difference in the shape and corresponding numerical values of the respective 10/20 and 15/30 curves. While only the results for these two networks are presented here, they are typical of results obtained when a variety of different network topologies were tested under different network loadings using the two implementations of the Heritsch algorithm. The conclusion



drawn from these results is that for a given network and specified updating cycle time there is no significant advantage in implementing the Heritsch algorithm synchronously as opposed to asynchronously (or vice versa). This conclusion has considerable impact on the physical design of a packet switching network, since it is not required to precisely synchronize the adoption of new best paths throughout the network in order to obtain the full benefits of the Heritsch algorithm. This translates to a reduced complexity in the design of the packet network terminal equipment.

#### 4. Effects Of User Message Lengths

One of the initial objectives of this study was to determine how the distribution of the lengths of user messages impacts the performance of a Distributed Routing Protocol. Since the simulation programs are constructed to operate on a predetermined packet length, the length of a user message is related to the number of packets which make up the message. In the simulations, the number of packets in each message is based upon a uniformly distributed random variable with the maximum and minimum values of the variable specified at the beginning of the simulation. The mean



value of the resulting distribution is used to control the interval between the generation of user messages. In this way the average number of packets per second entering the network is maintained as a constant for each run of the simulation, and the mean number of packets that are contained in each message can be increased arbitrarily.

The results of this investigation are plotted on each of the graphs presented in Appendix F. The graphs contain the results found when the mean number of packets in a message was 5.5 and 10.5, corresponding to maximum message lengths of 10 and 20 packet, respectively. No significant difference in the performance of either the Djikstra or the Heritsch protocols was found as a result of increasing the length of the user messages. Mean packet values of 1, 3.5 and 7.5 were also investigated but are not presented here since the results obtained do not differ substantially from those mentioned above.

## B. SYNOPSIS OF RESULTS

It is not possible to conclude that a particular Distributed Routing Protocol (Djikstra or Heritsch) exhibits better overall performance characteristics than the other. Each algorithm has advantages and disadvantages which must



be considered on the basis of the network in which the protocol is to be implemented. Certainly, if optimal routing is a priority of the network, then the Djikstra algorithm is superior. However, if non-optimal routing is acceptable and complexity of terminal equipment is a consideration then the Heritsch algorithm has distinct advantages if implemented asynchronously.

The final conclusion of this study is that the length of user messages does not degrade the performance of either protocol much when the average number of packets entering the network per unit of time is relatively constant. Thus the interspersion of long and short user messages is not a factor in the design of a packet switching network.

Lastly, it appears in the context of the NTDS communications network that the Djikstra algorithm is the protocol of choice should the NTDS be converted to a packet switching network. While the asynchronous advantages of the Heritsch algorithm appear desirable for this application, the increasing amount of information the NTDS is being required to throughput, points to the adoption of a protocol which requires a minimum of network capacity to operate. Additionally, since units of the fleet are not constrained





by the size and complexity of the terminal equipment which is required to maintain a synchronized network (as compared to a man-pack version of a packet switching network) the choice of the Dijkstra algorithm for NTDS applications is reasonable.



## APPENDIX A

### AVERAGE DELAY PER PACKET

The unit of measure used in this study to compare the relative performance of routing protocols in a given network is the average delay per packet ( $T_p$ ). The derivation of the relation of this measure to the link utilization factors of the network is provided here and is based upon material presented in Gross and Harris [Ref. 5]. and Kleinrock [Ref. 6].

One of the basic parameters in queuing theory is the utilization factor ( $\rho$ ) which is defined as the average arrival rate of customer (eg. packets and updates) at a service center (eg. link) multiplied by the average time required to service (eg. transmit) the customer. In general this is expressed as

$$\rho = \lambda x \quad (A-1)$$

where

- $\lambda$  = the average arrival rate of the customers
- $x$  = the average time required to service a  
a customer

For this derivation the subscripts p and u are used to indicate that a particular variable is referred to packets



or updates respectively. Thus the utilization factor for packets over the  $i$ -th link is expressed as

$$p_{pi} = l_{pi} x_{pi} \quad (a-2)$$

where

$l_{pi}$  = the average number of packets per second arriving for transmission over a link.

For an M/M/1 queue, the term  $x_{pi}$  can be replaced by the term  $1 / uC_i$ , where  $u$  represents the percentage of a packet which is represented by 1 bit (ie.  $1 / u$  represents the length of a packet in bits) and  $C_i$  is the number of bits per second which can be serviced by the  $i$ -th link. Equation (A-2) can then be rewritten as

$$p_{pi} = \frac{l_{pi}}{uC_i} \quad (A-3)$$

Moreover, for M/M/1 systems (ie. a system with customers arriving at an exponentially distributed rate and the service time per customer is exponentially distributed) the expected time a packet spends in the  $i$ -th link's queue before servicing begins can be expressed as



$$W_{qpi} = \frac{\frac{1}{uC_i} / \frac{1}{p_i}}{\frac{1}{uC_i} - \frac{1}{p_i}} \quad (A-4)$$

and the expected delay for the delivery of a packet over a link is

$$W_{pi} = W_{qpi} + \frac{1}{uC_i} \quad (A-5)$$

which is to say that the expected delivery delay for a packet is the sum of the expected time the packet spent in the service queue plus the time required to service the packet.

The assumption is made for the remainder of the derivation that Equation (A-4) will provide a fair representation of the expected delay time for a packet when the service time per packet is fixed instead of probabilistic in its nature. However, since two types of messages (updates and packets) with different fixed service times are allowed to enter a link, the time available for the link to service packets is reduced by the amount of time the link is busy servicing updates. Thus Equation (A-4) must still be modified to reflect the system perturbation due to the loss of available packet service time.





Consider the case where  $x_{ui}$  is the time required to service an update message and  $t_{ui}$  is the interval between the arrival of update messages at the  $i$ -th link. The arrival rate of updates at the link ( $l_{ui}$ ) is equal to  $(1 / t_{ui})$ . Using Equation (A-2), modified to reflect its application to update message, the utilization factor for updates becomes

$$p_{ui} = \frac{x_{ui}}{t_{ui}} \quad (A-6)$$

The fundamental interpretation of the term  $uCi$  in Equation (A-4) is the maximum average number of packets which can be transmitted per second over the  $i$ -th link. Only a fraction  $((t_{ui} - x_{ui}) / t_{ui})$  of the time is available for packets, however, when updates must also be transmitted. Accordingly, we must reduce  $uCi$  by the factor

$$1 - \frac{x_{ui}}{t_{ui}} = 1 - p_{ui} \quad (A-7)$$

which is equivalent to reducing  $u$  to  $u'$ , where

$$u' = u (1 - p_{ui}) \quad (A-8)$$



Replacing  $u$  with  $u'$  in Equation (A-4), a new expression for  $W_{pi}$  (Equation (A-5)) is obtained

$$W_{pi} = \left[ \frac{\frac{1}{p_i} / (u C_i (1 - p_{ui}))}{u C_i (1 - p_{ui}) - \frac{1}{p_i}} + \frac{1}{u C_i} \right] \quad (A-9)$$

From Kleinrock, [Ref. 6]. the average packet delay ( $T_p$ ) for a network of service centers is expressed as

$$T_p = \sum_{i=1}^k \frac{\frac{1}{p_i}}{g} W_{pi} \quad (A-10)$$

where

$g$  = average total number of packets  
per second entering the  
network

$k$  = number of links in the network

Substituting Equation (A-5) into equation (A-10) the expression for average delay time for a packet in the network becomes

$$T_p = \frac{1}{g} \sum_{i=1}^k \left[ \frac{\frac{1}{p_i} \frac{1}{p_i} / (u C_i (1 - p_{ui}))}{u C_i (1 - p_{ui}) - \frac{1}{p_i}} + \frac{1}{u C_i} \right] \quad (A-11)$$

After some simplification this becomes



$$T_p = -\frac{1}{g} \sum_{i=1}^k \left[ \frac{p_{pi}^2 / (1 - p_{ui})}{1 - p_{ui} - p_{pi}} + p_{pi} \right] \quad (A-12)$$

Equation (A-12) represents a method of relating the network capacity which is utilized by a routing protocol and the traffic loading level of the network to the average packet delay. For the simulation work presented in this study the utilization factors ( $p_{ui}$  and  $p_{pi}$ ) were measured directly and the network loading ( $g$ ) was an input parameter to the simulation.

The reader should note that Equation (A-12) is valid only for comparing the performance of protocols and not for calculation of the actual performance of a protocol.



APPENDIX B  
NETWORK CONFIGURATIONS

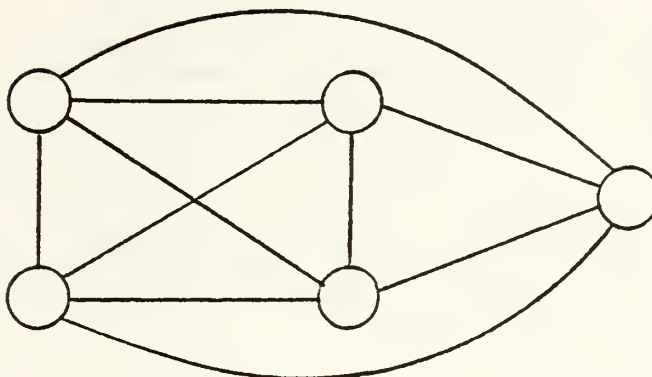


Fig. B.1. The 5/10 Network

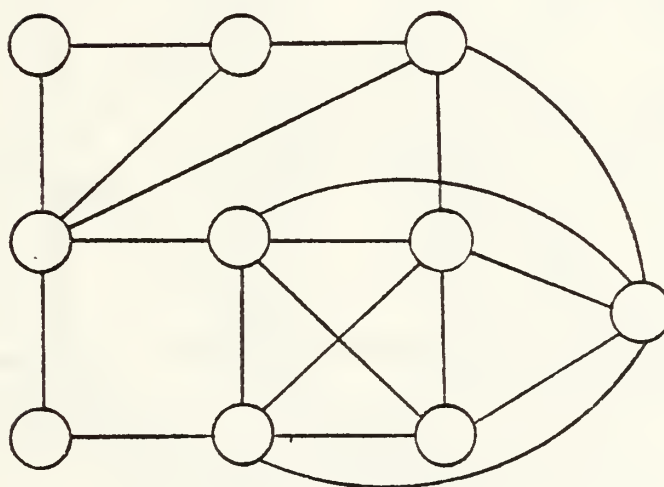


Fig. B.2. The 10/20 Network





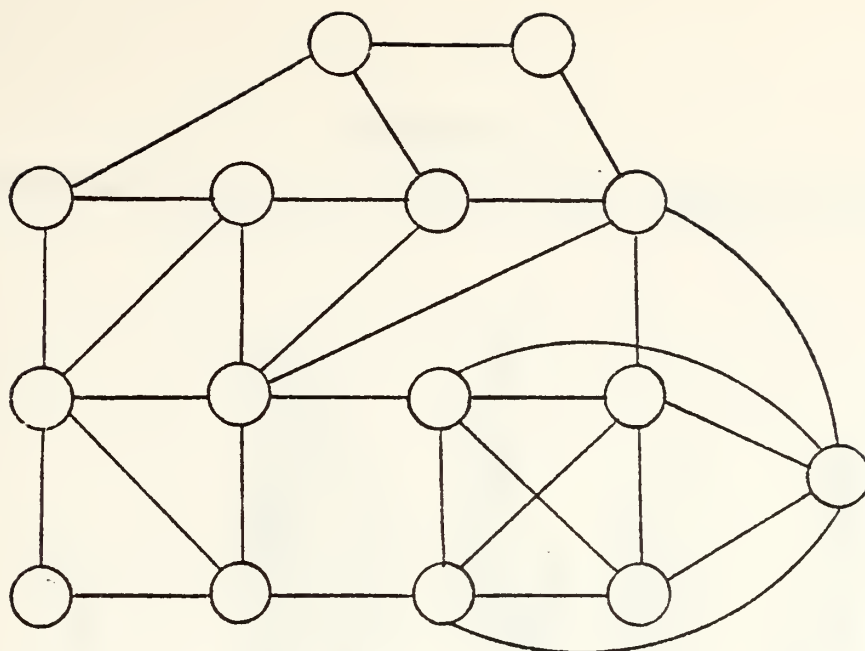


Fig. B.3. The 15/30 Network

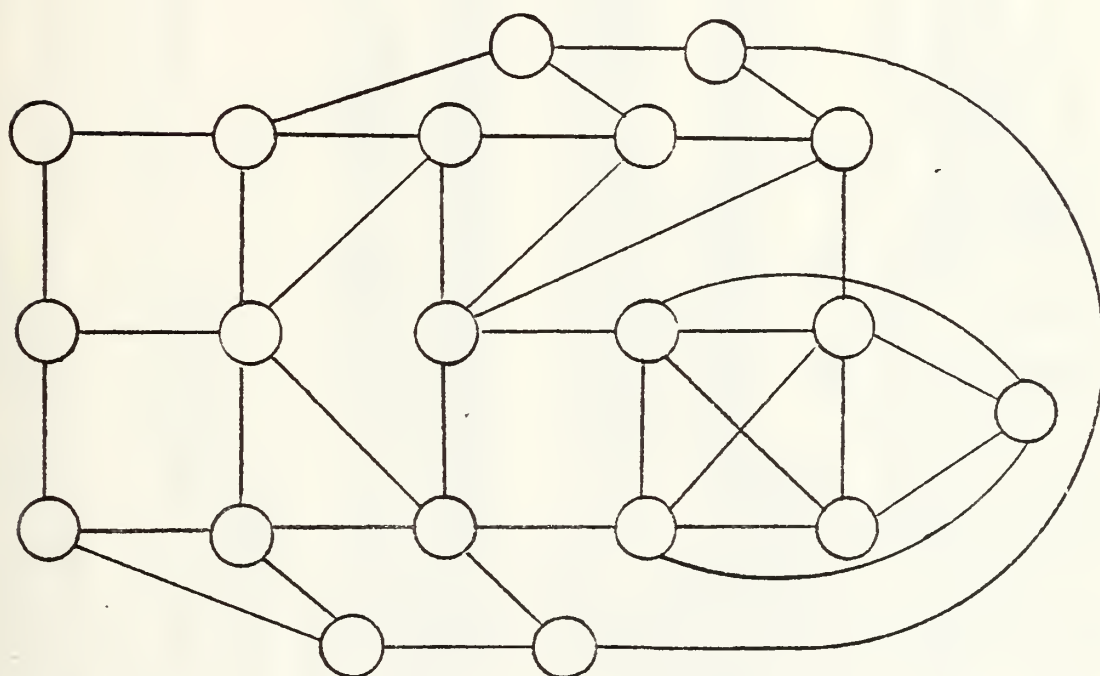


Fig. B.4. The 20/40 Network



HERITSCH ALGORITHM (SYNCHRONOUS): PROGRAM LISTING

```

//LENGERIC JCB (1611,014C), 'LENGERIC 1101', CLASS=C
//*MAIN ORG=NP GVM1.1611P, LINES=(50)
//*FORMAT PR, DDNAME=, DEST=LOCAL
// EXEC SIM23CLG, REGION.GO=3072K, PARM.GO='MAP, SIZE=760K'
//SYSPRINT DD SYSCUT=A
//SIM, SYSD CD *
//PREAMBLE
..
.. THIS PROGRAM SIMULATES THE HERITSH DISTRIBUTED ROUTING
.. PROTOCCL (SYNCHRONOUS).
..
.. NORMALLY MODE IS INTEGER
.. GENERATE LIST ROUTINES
..
PERMANENT ENTITIES
EVERY NODE HAS A TRANSMIT.PERCENT, A RECEIVE.PERCENT, A GROUP, UPDATES
A FAMILY, A U.TOTAL, A AVE.NUMBER, UPDATES, A ALT.AVE.NUMBER, UPDATES
AND A PKTS.RELAYED, OWNS AN UPDATE.OUT.QUEUE, A PACKET.OUT.QUEUE,
A TIME.QUEUE AND A LNK.FLAG
DEFINE TRANSMIT.PERCENT, RECEIVE.PERCENT, AVE.NUMBER, UPDATES,
AND ALT.AVE.NUMBER, UPDATES AS REAL VARIABLES
DEFINE UPDATE.OUT.QUEUE AND PACKET.OUT.QUEUE AS FIFO SETS
..
TEMPORARY ENTITIES
EVERY MESSAGE HAS A TYPE, A RELAYER, A NEXT.STOP, A DESTINATION,
AN INFO1, AN INFO2, AN INFO3, AN INFO4, AN INFO5, A QUEUE.ENTRY.TIME,
AN ORIG.TIME, A LINK.ENTRY.TIME, AND A TOT.QUEUE.TIME
AND MAY BELONG TO A UPDATE.OUT.QUEUE, A PACKET.OUT.QUEUE,
AND A LNK.FLAG
DEFINE ORIG.TIME AS A REAL VARIABLE
DEFINE LINK.ENTRY.TIME AND TOT.QUEUE.TIME AS REAL VARIABLES
DEFINE INFO4 AND QUEUE.ENTRY.TIME AS A REAL VARIABLE
EVERY PACKET HAS A NUMBER, AN ENTRY.TIME, A PAC.NEIGHBOR AND MAY
BELONG TO A TIME.QUEUE
DEFINE TIME.QUEUE AS A LIFO SET
DEFINE ENTRY.TIME AS A REAL VARIABLE
..
EVENT NOTICES INCLUDE REPORT.RESULTS, QU.SAMPLER, SAMPLE,
COMPUTE.CV, ADOPT.NEW.BEST.PATH
EVERY NEW.UPDATE.MESSAGE HAS A SENDING.NODE, AND A TYPE.MESSAGE
EVERY UPDATE.ARRIVES HAS AN ID.MESSAGE.NUMBER
EVERY CONT.UPDATE.MESSAGE HAS A LAST.NODE, A NEXT.NODE, A NET.CV,
A SOURCE, A FAMILY, A HOP.CNT AND A GR.OUP
EVERY PACKET.ARRIVES HAS AN ID.NUMBER
EVERY CON.PACKET.MESSAGE HAS AN IDENT.MESSAGE.NUMBER
EVERY NEW.PACKET.MESSAGE HAS A T.MESSAGE
EVERY COMPLETED.TRIP HAS A MES.NUM
..

```



```

DEFINE UP.DATE.PERIOD, PROCESSING.TIME, PKT.XMN.TIME AND TIME.LIMIT
AS REAL VARIABLES
DEFINE TRNS.PCNT AND RCV.PCNT AS REAL VARIABLES
DEFINE LINKS AS A VARIABLE
DEFINE MSG.HLT AS A VARIABLE
DEFINE NEIGHBOR.LIST AS A 3-DIMENSIONAL INTEGER ARRAY
DEFINE BEST.PATH AS A 3-DIMENSIONAL INTEGER ARRAY
DEFINE CHANNEL.VALUE TC MEAN INFO1
DEFINE FAM.LY TO MEAN INFO2
DEFINE GRPS TO MEAN INFO5
DEFINE FMLS AND NGFS AS VARIABLES
DEFINE LINK.ABLE AS A 2-DIMENSIONAL ARRAY
DEFINE LINK.MONITR AS A 3-DIMENSIONAL ARRAY
DEFINE TRACKER AS A 2-DIMENSIONAL REAL ARRAY
DEFINE CLOCK.DATA AS A 2-DIMENSIONAL REAL ARRAY
DEFINE HOP.CCUNT AS A 2-DIMENSIONAL REAL ARRAY
DEFINE PKT.SMP.SET AS A 2-DIMENSIONAL ARRAY
DEFINE UP.SMP.SET AS A 2-DIMENSIONAL ARRAY
DEFINE UP.QU.DISTR AS A 1-DIMENSIONAL ARRAY
DEFINE FAM.CF.GRP AS A 1-DIMENSIONAL ARRAY
DEFINE IDLE TO MEAN 0
DEFINE BUSY TO MEAN 1
DEFINE PACKET TO MEAN 1
DEFINE MSG.GENERATION.INTERVAL, MIN.PKTS.PER.MSG,
MAX.PKTS.PER.MSG AS REAL VARIABLES
DEFINE EST.MAX.NR.MSGS AND NEW.INFO1
AS VARIABLES
DEFINE TRANS.NUMBER TO MEAN INFO2
DEFINE PACKS.HOPPED TO MEAN INFO3
DEFINE RELEASE.TIME TO MEAN INFO4
DEFINE FM.GP TO MEAN INFO5
DEFINE YES TO MEAN 1
DEFINE NO TC MEAN 0
DEFINE UPDATE TO MEAN 1
DEFINE TRAF.LIMIT AS A VARIABLE
DEFINE WINDCW AS A REAL VARIABLE
DEFINE UP.PAC.RATIO AS A REAL VARIABLE
DEFINE PRNT AS A VARIABLE
DEFINE IN.GROUP, IN.FAMILY, SELECTOR AS REAL VARIABLES
DEFINE NET.U.LINKS, IN.UP.STARTS, MAX.U.HOPS AS VARIABLES
DEFINE TI.MER AS A REAL VARIABLE
DEFINE SMP.LINKS, NO.OF.SAMPLES, SMP.CNTR AS VARIABLES
DEFINE EARLIEST.UPDATE AND LATEST.UPDATE AS REAL VARIABLES
DEFINE U.XMN.TIME AS REAL
DEFINE PEFK AS A VARIABLE
DEFINE TOTAL.NUMBER.CYCLES AND NUMBER.CYCLES.COMPLETED AS
REAL VARIABLES

```



```

DEFINE MAX.LINKS.PER.NODE AS VARIABLE
DEFINE TIME.ELAPSED AND CYCLE.TIME AS REAL VARIABLES
DEFINE P.FLOW1, P.FLOW2, U.FLOW1 AND U.FLOW2 AS REAL VARIABLES
DEFINE LONGEST.PATH AS VARIABLE
DEFINE LINK.TIMER AS 4-DIMENSIONAL REAL ARRAY
DEFINE LINK.NODE.RAT AS REAL VARIABLE
DEFINE P.FLOW.TOTAL, U.FLOW.TOTAL, AVE.P.FLOW, AVE.U.FLOW AND
DE PCNT.U.FLOW AS REAL VARIABLES
DEFINE AVE.NETWORK.FLOW AS REAL VARIABLE
DEFINE SPECIFY.OUTPUT AS VARIABLE
DEFINE RERUN AS VARIABLE
DEFINE PKTS.PER.SEC.AVE AS REAL VARIABLE
DEFINE NODE.FACTOR AS VARIABLE
DEFINE HISTOGRAM AS 1-DIMENSIONAL ARRAY
DEFINE P1.DELAY, P2.DELAY, U1.DELAY, U2.DELAY,
TOTAL.DELAY, LINK1.FLOW, LINK2.FLOW AND
AVE.DELAY.PER.PKT AS REAL VARIABLES
DEFINE RATIOC.STRANDED AS REAL VARIABLE
DEFINE PKTS.HALF AND PKTS.END AS VARIABLES
DEFINE DEST.COUNT AND GEN.COUNT AS VARIABLES
DEFINE STRANDED.WAIT AND TRANSIT.TIME AS REAL VARIABLES
DEFINE T.IN.LINK AND Q.IN.LINK AS REAL VARIABLES
END ** OF PREAMBLE
**
** MAIN
**
LEFT LINES.V = 79
SKIP 2 OUTPUT LINES
**
PRINT 4 LINES AS FOLLOWS
##### HERITSCH UPDATE ALGORITHM: SYNCHRONOUS VERSION #####
##### PACKET GENERATION RATE : FIXED #####
##### INCREMENT FOR PKTS PER MSG : HARMONIC #####
##### NORMALIZE: AVE.PKTS.PER.MSG.PER.NODE #####
**
SKIP 2 OUTPUT LINES
**
THE "MAIN" ROUTINE "CALLS" THE SUBROUTINE "INITIALIZATION".
** "INITIALIZATION" SETS THE VALUE OF INPUT VARIABLES
** WHICH WILL REMAIN CONSTANT FOR ALL RUNS OF THIS
** SIMULATION. THIS ALLOWS THE "MAIN" ROUTINE TO ACT AS A
** "DRIVER" ROUTINE FOR SIMULATION. THE "MAIN" CAN BE
** STRUCTURED TO CHANGE CERTAIN CONDITIONS OF THE SIMULATION
** AND RERUN THE SIMULATION AGAIN.
**
DEFINE INC.PKTS.PER.MSG, LIMIT.PKTS.PER.MSG, AVE.PKTS.PER.MSG,
PKTS.PER.SEC.MIN, PKTS.PER.SEC.INC, PKTS.PER.SEC.MAX

```





```

AS REAL VARIABLES
..
.. SET THE MAXIMUM, INCREMENT AND MINIMUM VALUES OF THE
.. VARIABLES WHICH ARE TO BE ITERATED.
..
.. BY MULTIPLYING PKTS.PER.SEC.( ) * NCDE.FACTOR THE RESULTS
.. OF THE SIMULATION CAN BE NORMALIZED SO THAT NETWORKS
.. WITH DIFFERENT NUMBERS OF NODES CAN BE COMPARED USING
.. "AVE.PKT.PER.SEC.NODE" AS A CONSTANT MEASURE OF
.. NETWORK LOADING. (EG. IF A 5 NODE NETWORK IS THE
.. COMPARISON BASE THEN A 10 NODE NETWORK HAS A NODE.FACTOR
.. = 2. # NOTE: NODE.FACTORS GREATER THAN 4 REQUIRE IN
.. EXCESS OF 3072K CF CORE TO RUN THE SIMULATION.
..
READ NCDE.FACTOR
..
LET MIN.PKTS.PER.MSG = 10.
LET INC.PKTS.PER.MSG = 10.
LET LIMIT.PKTS.PER.MSG = 21.
..
LET PKTS.PER.SEC.MIN = 50. * NODE.FACTOR
LET PKTS.PER.SEC.INC = 50. * NODE.FACTOR
LET PKTS.PER.SEC.MAX = 500. * NODE.FACTOR
..
LET PKTS.PER.SEC.AVE = PKTS.PER.SEC.MIN
..
THE FOLLOWING ARRAYS WILL CONTAIN THE 'X' AND 'Y' VALUES OF
DATA TO BE GRAPHED.
..
"ITERATE" IS THE NUMBER OF TIMES THE VALUE OF "MAX.PKTS.PER.MSG"
IS CHANGED AND THE SIMULATION REINITIATED.
"POINTS" IS THE NUMBER OF TIMES THE VALUE OF "PKTS.PER.SEC.AVE"
IS CHANGED AND THE SIMULATION RERUN. THE
TOTAL NUMBER OF TIMES THE SIMULATION RUNS IS
( ITERATE * POINTS ).
..
ITERATE = 2
POINTS = 10
..
LET AVE.PKTS.PER.MSG = (1.0 + MIN.PKTS.PER.MSG) / 2.
LET MSG.GENERATION.INTERVAL = AVE.PKTS.PER.MSG / PKTS.PER.SEC.AVE
..
THE VALUE OF "MAX.PKTS.PER.MSG" WILL BE INCREMENTED USING A
HARMONIC SERIES.
..
MAX.PKTS.PER.MSG = MIN.PKTS.PER.MSG
..
"RERUN" CONTROLS THE PRINTING OF THE NEIGHBOR AND CV

```



```

''      LISTING.  THE LISTING IS PRINTED ONLY FOR INITIAL
''      EXECUTION OF THE PROGRAM.
''
LET RERUN = 0
PERFORM INITIALIZATION
RELEASE INITIALIZATION
LET EST.MAX.NR.MSGS = 2 * INT.F( TIME.LIMIT / ( 1.0 /
PKTS.PER.SEC.MAX ) )
RESERVE TRACER ( *, * ) AS EST.MAX.NR.MSGS BY 2
LET RERUN = 1
''
''      THESE STATEMENTS CAUSE THE VALUES OF "ITERATE" AND
''      "POINTS" TO BE WRITTEN TO THE MASS STORAGE SYSTEM
''      FOR LATER RETRIEVAL BY A PLOTTING ROUTINE.
''
USE UNIT 8 FOR OUTPUT
WRITE ITERATE AS I 4
WRITE POINTS AS /, I 4
USE UNIT 6 FOR OUTPUT
''
''      SCHEDULE INITIAL EVENTS
''
''      SCHEDULE THE FIRST UPDATE FOR EACH NODE (NEW.UPDATE.MESSAGE)
''      COMPUTE CHANNEL VALUES FOR THIS UPDATE (COMPUTE.CV)
''      SCHEDULE THE FIRST REPORT (REPORT.RESULTS)
''      SCHEDULE THE FIRST MESSAGE GENERATION (NEW.PACKET.MESSAGE)
''      SCHEDULE A TEST FOR MAX QUEUES HALF WAY THRU RUN (QU.SAMPLER)
''
''      "TOTAL.POINTS" COUNTS THE NUMBER OF TIMES THE SIMULATION IS
''      RUN.
''
LET TOTAL.PCINTS = 0
''
''      DO IT AGAIN
''
LET TOTAL.PCINTS = TOTAL.POINTS + 1
''
FOR EACH NODE, DO
  SCHEDULE A NEW.UPDATE.MESSAGE GIVEN NODE, UPDATE IN ( UNIFORM.F
  ( 0.0, UP.DATE.PERIOD, 1 ) ) UNITS
  LOOP
''
SCHEDULE A COMPUTE.CV AT 0.00
SCHEDULE A REPORT.RESULTS IN ( TIME.LIMIT / 4. ) UNITS
SCHEDULE A NEW.PACKET.MESSAGE GIVEN PACKET IN ( 2 * .1 +

```



```

EXPONENTIAL.F( MSG.GENERATION.INTERVAL, 5 ) ) UNITS
SCHEDULE A QU.SAMPLER IN ( TIME.LIMIT / 2. ) UNITS
..
START SIMULATION
..
..   THE NEXT GROUP OF STATEMENTS ZEROIZE ALL GLOBAL VARIABLES AND
..   ARRAYS IN PREPARATION FOR A RERUN OF THE SIMULATION.
..
TIME.V = 0.0
LET MSG.TOTAL = 0
LET MSG.HLT = 0
LET NET.U.LINKS = 0
LET UP.STARTS = 0
LET MAX.U.HCPS = 0
LET SMP.CNTR = 0
LET PEEK = 0
LET TOTAL.NUMBER.CYCLES = 0.0
LET NUMBER.CYCLES.COMPLETED = 0.0
LET TIME.ELAPSED = 0.0
LET LONGEST.PATH = 0
LET PKTS.HALF = 0
LET PKTS.END = 0
LET DEST.COUNT = 0
LET GEN.COUNT = 0
LET TRANSIT.TIME = 0.0
LET STRANDEC.WAIT = 0.0
LET T.IN.LINK = 0.0
LET Q.IN.LINK = 0.0
..
FOR A = 1 TC ( 2 * LINKS ), DO
FOR B = 1 TO ( 2 * LINKS ), DO
FOR C = 1 TC 6, DO
LET LINK.MONITOR( A, B, C ) = 0
LOOP
LOOP
LOOP
FOR A = 1 TO 2, DO
FOR B = 1 TO ( N.NODE ), CO
FOR C = 1 TO ( N.NCDE ), DO
FOR D = 1 TO 4, DO
LET LINK.TIMER( A, B, C, D ) = 0.0
LOOP
LOOP
LOOP
LOOP
FOR A = 1 TO ( 10 * N.NODE ), DO
FOR B = 1 TO 2, CO
LET HOP.COUNT( A, B ) = 0

```



```

      LET CLOCK.DATA( A, B ) = 0
      LCCP
    LOOP
      FOR A = 1 TO EST.MAX.NR.MSGS, DO
        FOR B = 1 TO 2, DO
          LET TRACER( A, B ) = 0
        LOOP
      LOOP
      FOR A = 1 TC 1000, DO
        LET PKT.QU.DISTR(A) = 0
        LET UP.QU.CISTR(A) = 0
      LOOP
      FOR A = 1 TC SMP.LINKS, DO
        FOR B = 1 TO 2, DO
          LET PKT.SMP.SET( A, B ) = 0
          LET UP.SMP.SET( A, B ) = 0
        LOOP
      LOOP
    ,
    RELEASE BEST.PATH( *, *, * )
    RELEASE NEIGHBOR.LIST( *, *, * )
    RELEASE HISTOGRAM( *, * )
    ,
    PERFCRM NEIGHBOR.INITIALIZATION
    ,
    LET PKTS.PER.SEC.AVE = PKTS.PER.SEC.AVE + PKTS.PER.SEC.INC
    ,
    IF PKTS.PER.SEC.AVE <= PKTS.PER.SEC.MAX
    ,
    LET MSG.GENERATION.INTERVAL = AVE.PKTS.PER.MSG / PKTS.PER.SEC.AVE
    ,
    IF SPECIFY.OUTPUT = 0
    ,
    SKIP 2 OUTPUT LINES
    ,
    PRINT 1 LINE AS FCLLCWS
    ,
    ##### SIMULATION RESTART #####
    ,
    SKIP 1 OUTPUT LINE
    ,
    PRINT 1 LINE WITH PKTS.PER.SEC.AVE AS FOLLOWS
    ,
    PKTS.PER.SEC.AVE = ***.***
    ,
    REGARDLESS
    ,
    GO DO.IT.AGAIN
    ,
    ELSE

```





```

.. LET PKTS.PER.SEC.AVE = PKTS.PER.SEC.MIN
.. LET MAX.PKTS.PER.MSG = MAX.PKTS.PER.MSG + INC.PKTS.PER.MSG
.. IF MAX.PKTS.PER.MSG <= LIMIT.PKTS.PER.MSG
.. LET AVE.PKTS.PER.MSG = (MAX.PKTS.PER.MSG + 1.0) / 2
.. LET MSG.GENERATION.INTERVAL = AVE.PKTS.PER.MSG / PKTS.PER.SEC.AVE
.. LET INC.PKTS.PER.MSG = INC.PKTS.PER.MSG + 1.0
.. IF SPECIFY.OUTPUT = 0
..
.. SKIP 2 OUTPUT LINES
.. PRINT 1 LINE AS FOLLOWS
.. @@@@@@@@@@@@@@@@@@ SIMULATION RESTART @@@@@@@@@@@@@@@@@@
..
.. SKIP 1 OUTPUT LINE
..
.. PRINT 2 LINES WITH MAX.PKTS.PER.MSG
.. AND PKTS.PER.SEC.AVE AS FOLLOWS
.. MAX.PKTS.PER.MSG = ***.***
.. PKTS.PER.SEC.AVE = ***.***
.. REGARDLESS
.. GO DO.IT.AGAIN
.. ELSE
.. SKIP 1 OUTPUT LINE
.. PRINT 1 LINE AS FOLLOWS
.. SIMULATION STOPS
..
.. STCP
..
.. END **CF MAIN
..
.. THIS ROUTINE INITIALIZES ALL THE VARIABLES IN THE SIMULATION.
.. BY PROPER STRUCTURING OF THIS ROUTINE AND THE "MAIN", THE
.. SIMULATION CAN BE MADE TO SUCCESSIVELY RERUN ITSELF USING
.. ANY NUMBER OF NEW INPUT PARAMETERS CN EACH RUN.
..
.. ROUTINE FOR INITIALIZATION
..
.. SPECIFY.OUTPUT IS AN INTEGER WHICH CONTROLS THE OUTPUT FORMAT.
.. 0 => ALL INPUT DATA ,THE QUARTERLY RESULTS OF THE
.. SIMULATION AND THE SPECIAL. OUTPUT SECTION
.. ARE PRINTED

```



```

.. 1 => ONLY THE INPUT DATA AND THE DATA SPECIFIED
.. BY THE PROGRAMMER IN "SPECIAL.OUTPUT"
.. ARE PRINTED OUT. QUARTERLY RESULTS OF
.. THE SIMULATION ARE NOT PRINTED.
.. 2 => ONLY THE DATA SPECIFIED IN "SPECIAL.OUTPUT"
.. IS PRINTED OUT.

LET SPECIFY.OUTPUT = 1
..
.. SET SOME VARIABLES
..
.. SET THE RANGE OF PACKETS PER MESSAGE ( MIN.PKTS.PER.MSG
.. AND MAX.PKTS.PER.MSG )
.. SET A LIMIT ON THE NUMBER OF MESSAGES GENERATED
.. DURING A RUN OF THE SIMULATION ( TRAF.LIMIT )
.. SET AN UPDATE MSG TO PACKET PROCESSING RATIO (U.PAC.RATIO)
.. SET AN UPDATE MSG TRANSMISSION TIME (U.XMN.TIME)
..
LET TRAF.LIMIT = 95000
LET UP.PAC.RATIO = .1
LET U.XMN.TIME = C.002
..
.. READ AND PRINT INPUT DATA
..
READ N.NODE
..
IF SPECIFY.OUTPUT <= 1
PRINT 2 LINES AS FOLLOWS
NODE TRANSMIT RECEIVE GROUP FAMILY
NO. FACTOR FACTOR (PGM #) (PGM #)
REGARDLESS
..
CREATE EVERY NODE
FOR EVERY NCDE
READ TRANSMIT.PERCENT(NODE), RECEIVE.PERCENT(NODE), GROUP(NODE),
FAMILY(NODE)
..
TRNS.PCNT AND RCV.PCNT ARE THE SUM CF TRANSMIT AND RECEIVE FACTORS.
GROUP NUMBERS ARE ADDED TO N.NODE TO GET PROGRAM GROUP NUMBERS.
FAMILY NUMBERS ARE ADDED TO N.NODE + THE HIGHEST GROUP NUMBER
..
WITHIN THE SIMULATION GROUPS AND FAMILIES ARE HANDLED AS IF
THEY WERE SUPER-NCDES. A USEFUL ANALOGY IS TO
ENVISION MANY SUB-NODES WITHIN A GROUP OR FAMILY SUPER-
NODE ACCESS TO THE SUB-NCDES IS CONTROLLED BY THE
THE SUPER-NODE'S "ADDRESS".
..
FOR I = 1 TO N.NODE, DC

```



```

LET TRNS.PCNT = TRNS.PCNT + TRANSMIT.PERCENT(I)
LET RCV.PCNT = RCV.PCNT + RECEIVE.PERCENT(I)
IF GRPS < GROUP(I)
  LET GRPS = GROUP(I)
REGARDLESS
..
.. SET PROGRAM GRP NUM
..
  LET GROUP(I) = GROUP(I) + N.NODE
  LOOP
  RESERVE FAM.CF.GRP (*) AS (GRPS + N.NODE + 25)
  FOR I = 1 TO N.NODE, DO
    IF FMLYS < FAMILY(I)
      LET FMLYS = FAMILY(I)
  REGARDLESS
..
.. SET PROGRAM FAM NUM
..
  LET FAMILY(I) = N.NODE + GRPS + FAMILY(I)
  LET FAM.OF.GRP (GROUP(I)) = FAMILY(I)
  LOOP
  LET NGFS = N.NODE + GRPS + FMLYS
  LET SPECIFY.OUTPUT <= 1
  FOR I = 1 TO N.NODE, DO
    PRINT 1 LINE WITH I, TRANSMIT.PERCENT(I), RECEIVE.PERCENT(I),
      (GROUP(I) - N.NODE), GROUP(I), (FAMILY(I) - N.NODE - GRPS)
    AND FAMILY(I) AS FOLLOWS
  **.*** **.*** **.***
..
  LOOP
  SKIP 1 OUTPUT LINE
REGARDLESS
..
READ UP.DATE.PERIOD
READ PROCESSING.TIME
READ PKT.XMN.TIME
READ TIME.LIMIT
READ WINDOW
..
LET CYCLE.TIME = 2 * UP.DATE.PERIOD
LET TOTAL.NUMBER.CYCLES = TIME.LIMIT / CYCLE.TIME
..
.. IN.GROUP MEANS THE PERCENTAGE OF GENERATED MESSAGES THAT WILL
.. NOT LEAVE ITS BASIC GROUP: SIMILARLY FOR IN.FAMILY.
.. NOTE: IF ALL NCDES ARE SPECIFIED TO BE MEMBERS OF THE
.. SAME GROUP AND FAMILY THEN VALUES OF IN.GROUP AND IN.FAMILY
.. ARE IGNORED BY THE PROGRAM.
..
READ IN.GROUP, IN.FAMILY

```









```

PRINT 1 LINE WITH TRAF.LIMIT AS FOLLOWS
MAX NUMBER OF MESSAGES GENERATED PER RUN IS *****
SKIP 1 OUTPUT LINE
..
PRINT 1 LINE WITH UP.DATE.PERIOD AS FOLLOWS
UPDATE PERIOD IS **.***** SEC.
SKIP 1 OUTPUT LINE
..
PRINT 1 LINE WITH PROCESSING.TIME AS FOLLOWS
PACKET PROCESSING TIME IN EACH NODE IS **.***** SEC.
SKIP 1 OUTPUT LINE
..
PRINT 1 LINE WITH PROCESSING.TIME * UP.PAC.RATIO AS FOLLOWS
UPDATE PROCESSING TIME IN EACH NODE IS **.***** SEC.
SKIP 1 OUTPUT LINE
..
PRINT 1 LINE WITH PKT.XMN.TIME AS FOLLOWS
TIME REQUIRED TO TRANSMIT A PACKET IS **.***** SEC.
SKIP 1 OUTPUT LINE
..
PRINT 1 LINE WITH U.XMN.TIME AS FOLLOWS
TIME REQUIRED TO TRANSMIT AN UPDATE IS **.***** SEC.
SKIP 1 OUTPUT LINE
..
PRINT 1 LINE WITH MSG.GENERATION.INTERVAL AS FOLLOWS.
MESSAGES ARE INITIATED AT AN AVERAGE INTERVAL OF **.***** SEC.
SKIP 1 OUTPUT LINE
..
PRINT 1 LINE WITH WINDOW AS FOLLOWS
CHANNEL VALUE CALCULATION WINDOW IS **.***** SEC.
SKIP 1 OUTPUT LINE
..
PRINT 1 LINE WITH MIN.PKTS.PER.MSG AND MAX.PKTS.PER.MSG AS FOLLOWS
EACH MESSAGE VARIES FROM **. TO **. PACKETS IN LENGTH
SKIP 1 OUTPUT LINE
..
PRINT 1 LINE WITH IN.GROUP AS FOLLOWS
AT LEAST **. % OF MESSAGES ARE TO NODES WITHIN A GROUP.
SKIP 1 OUTPUT LINE
..
PRINT 1 LINE WITH IN.FAMILY AS FOLLOWS
AT LEAST **. % OF MESSAGES ARE TO NODES WITHIN A FAMILY
SKIP 1 OUTPUT LINE
..
PRINT 1 LINE WITH TOTAL.NUMBER.CYCLES AS FOLLOWS
TOTAL NUMBER OF UPDATE CYCLES POSSIBLE FOR THIS RUN IS *****
SKIP 1 OUTPUT LINE
..

```



```

PRINT 1 LINE WITH CYCLE.TIME AS FOLLOWS
CYCLE TIME IS ****.***** SEC.
SKIP 1 OUTPUT LINE
..
PRINT 1 LINE WITH NODE.FACTOR AS FOLLOWS
NODE.FACTOR = ***
SKIP 1 OUTPUT LINE
..
REGARDLESS
..
..   ARRAYS ARE RESERVED AS FOLLOWS
..
RESERVE LINK.ABLE(*,*) AS LINKS BY 2
RESERVE LINK.MONITOR(*,*,*) AS (2*LINKS) BY (2*LINKS) BY 6
RESERVE HOP.CCUNT(*,*) AS ( 10 * N.NODE ) BY 2
RESERVE CLOCK.DATA(*,*,*) AS ( 10 * N.NODE ) BY 2
RESERVE PKT.SMP.SET(*,*) AS SMP.LINKS BY 2
RESERVE UP.SMP.SET(*,*) AS SMP.LINKS BY 2
RESERVE PKT.QU.DISTR(*) AS 1000
RESERVE UP.QU.DISTR(*) AS 1000
RESERVE LINK.TIMER(*,*,*,*) AS 2 BY (N.NODE) BY (N.NODE) BY 4
..
IF SPECIFY.OUTPUT <= 1
..
PRINT 1 LINE AS FOLLOWS
LINKS
..
REGARDLESS
..
FOR I = 1 TO LINKS, DO
  FOR J = 1 TO 2, READ LINK.ABLE(I,J)
  ..
  IF SPECIFY.OUTPUT <= 1
  ..
    PRINT 1 LINE WITH LINK.ABLE(I,1), LINK.ABLE(I,2) AS FOLLOWS
    ** - **
  ..
  REGARDLESS
  ..
  LOOP
  ..
PERFORM NEIGHBOR.INITIALIZATION
..
RETURN
END .. OF INITIALIZATION
..
..   THE FOLLOWING SUBROUTINE IDENTIFIES NEIGHBORS, SETS

```



```

**      INITIAL CV'S, AND PRINTS THE NEIGHBOR LIST AND
**      INITIAL CV'S.
**
ROUTINE FOR NEIGHBCR.INITIALIZATION
**
RESERVE HISTCGRAM( * ) AS 10
RESERVE BEST.PATH(*,*,*) AS NGFS BY NGFS BY 4
**
FOR I = 1 TO NGFS, DO
  LET BEST.PATH (I,I,1) = 1
  LET BEST.PATH (I,I,3) = 1
  LOOP
RESERVE NEIGHBOR.LIST(*,*,*) AS N.NODE BY MAX.LINKS.PER.NODE BY 3
FOR I = 1 TO LINKS, DO
  FOR J = 1 TO MAX.LINKS.PER.NODE, DO
    IF NEIGHBOR.LIST(LINK.ABLE(I,1),J,1) = 0
      LET NEIGHBOR.LIST(LINK.ABLE(I,1),J,1) = LINK.ABLE(I,2)
      LET NEIGHBOR.LIST(LINK.ABLE(I,1),J,3) = 1
      LET M = J
      GO NEXT STEP
    ELSE
      LOOP
  NEXT STEP
  FOR J = 1 TO MAX.LINKS.PER.NODE, DC
    IF NEIGHBOR.LIST(LINK.ABLE(I,2),J,1) = 0
      LET NEIGHBOR.LIST(LINK.ABLE(I,2),J,1) = LINK.ABLE(I,1)
      LET NEIGHBOR.LIST(LINK.ABLE(I,2),J,3) = 1
      GO LAST STEP
    ELSE
      LOOP
  LAST STEP
  LET NEIGHBOR.LIST(LINK.ABLE(I,1),M,2) = YES
  LET NEIGHBOR.LIST(LINK.ABLE(I,2),J,2) = YES
  LOOP
**
IF SPECIFY.OUTPUT = 0 AND RERUN = 0
**
  SKIP 3 OUTPUT LINES
  PRINT 1 LINE AS FOLLOWS
  NEIGHBORS AND CHANNEL VALUES
  FOR I = 1 TO N.NCDE, DO
    SKIP 1 OUTPUT LINE
    PRINT 1 LINE WITH I AS FOLLOWS
    NODE ** NEIGHBORS AND CV
    FOR J = 1 TO MAX.LINKS.PER.NODE, DO
      PRINT 1 LINE WITH NEIGHBOR.LIST(I,J,1) AND NEIGHBOR.LIST(I,J,3)
      AS FOLLOWS
      **
      **

```



```

      LOOP
      LOOP
      REGARDLESS
      **
      RETURN
      END ** OF NEIGHBOR. INITIALIZATION
      **
      ** THIS ROUTINE HALTS THE PROGRAM AND GIVES SEVERAL STATISTICAL
      ** REPORTS ON THE STATUS OF THE SIMULATION. AFTER FOUR REPORTS
      ** THE ROUTINE RETURNS CCNTROL OF THE PROGRAM TO THE "MAIN".
      **
      ** EVENT REPORT RESULTS
      ** DEFINE TOT.HOPS, TOT.PACKETS, TOT.HALF.PKTS, DELIVERED
      ** AND DLVRD.AT.HALF AS VARIABLES
      ** DEFINE AVE.TIME AND AVE.NODES.HOPPED AS REAL VARIABLES
      ** DEFINE RATIO AND IDEAL.TIME AS REAL VARIABLES
      ** DEFINE P.Y AND U.Y AS REAL VARIABLES
      ** DEFINE U.SD,P.SD,U.XR,P.XR,U.Z2,P.Z2,U.Z2SUM,P.Z2SUM AS REAL VARIABLES
      **
      ** PEEK CCUNT THE FOUR REPORTS
      ** TOT.PACKETS SUMS THE TOTAL PKTS GENERATED UP TO THIS POINT
      ** DELIVERED SUMS THE TOTAL PKTS REACHING THEIR DESTINATION
      ** TOT.HOPS SUMS ALL HOPS MADE BY ALL PKTS
      ** U.SUM AND P.SUM ARE THE SUMS OF THE SAMPLED Q SIZES
      ** U.X AND P.X ARE THE TOTAL NUMBER OF SAMPLES
      ** U.Z2SUM AND P.Z2SUM ARE THE SUMS OF THE SAMPLE SIZES SQUARED
      **
      LET PEEK=PEEK+1
      LET TOT.PACKETS = 0
      LET DELIVERED = 0
      LET TOT.HOPS = 0
      LET P.SUM = 0
      LET U.SUM = 0
      LET P.X = 0
      LET U.X = 0
      LET P.Z2SUM = 0.0
      LET U.Z2SUM = 0.0
      **
      ** COMPUTE THE NUMBER OF UPDATE CYCLES WHICH HAVE BEEN COMPLETED
      ** AT EACH REPCRT INTERVAL.
      **
      IF PEEK = 1
      LET TIME.ELAPSED = TIME.LIMIT / 4
      LET NUMBER.CYCLES.COMPLETED = TIME.ELAPSED / CYCLE.TIME
      REGARDLESS

```





```

IF PEEK = 2
  LET TIME.ELAPSED = TIME.LIMIT / 2
  LET NUMBER.CYCLES.COMPLETED = TIME.ELAPSED / CYCLE.TIME
REGARDLESS
IF PEEK = 3
  LET TIME.ELAPSED = ( 3 * TIME.LIMIT ) / 4
  LET NUMBER.CYCLES.COMPLETED = TIME.ELAPSED / CYCLE.TIME
REGARDLESS
IF PEEK = 4
  LET TIME.ELAPSED = TIME.LIMIT
  LET NUMBER.CYCLES.COMPLETED = TIME.ELAPSED / CYCLE.TIME
REGARDLESS
,,
,, PRINT BP NEIGHBORS AND CV
,,
,, IF SPECIFY.OUTPUT = 0
,,
  IF PRNT > 0
    SKIP 3 OUTPUT LINES
    FOR I = 1 TO N.NODE, DC
      SKIP 1 OUTPUT LINE
      PRINT 1 LINE WITH I AS FOLLOWS
      BEST PATHS FROM NCDE ** TO -- DESTINATION - BP.NEIGHBOR - CV FRM BP.NODE
      FOR J = 1 TO N.NODE, CO
        IF (GROUP(I) = GROUP(J) AND I NE J)
          PRINT 1 LINE WITH J, BEST.PATH(I,J,1), BEST.PATH(I,J,2)
          AS FOLLOWS
          **
          **
          **
          REGARDLESS
          LOOP
          FOR J = (N.NODE+1) TO NGFS, DO
            IF (GROUP(I) NE J AND FAMILY(I) NE J AND J > N.NODE)
              IF BEST.PATH(I,J,1) NE 0
                IF (FAM.OF.GRP{J} NE FAMILY(I) AND J <= (N.NODE + GRPS))
                  GO OMIT.PRINT
                ELSE
                  PRINT 1 LINE WITH J, BEST.PATH(I,J,1), BEST.PATH(I,J,2)
                  AS FOLLOWS
                  **
                  **
                  **
          OMIT.PRINT,
          REGARDLESS
          REGARDLESS
          LOOP
          LOOP
          REGARDLESS
          REGARDLESS
          **
          **
          **

```



```

..      CCUNT PKTS CREATED AND DELIVERED
..
FOR I = 1 TO NEW.MSG.TOTAL, DO
  LET TOT.PACKETS = TOT.PACKETS + TRACER (I,1)
  LET DELIVERED = DELIVERED + TRACER (I,2)
LOOP
..
..      COMPUTE THE AVERAGE NUMBER OF UPDATES GENERATED BY EACH NODE
..      PER UPDATE CYCLE PER DESTINATION.
..
FOR J = 1 TO N.NODE, DO
  LET AVE.NUMBER.UPDATES(J) = (( U.TOTAL(J) - NUMBER.CYCLES.COMPLETED)
    / ( N.NODE - 1 )) * ( 1 / NUMBER.CYCLES.COMPLETED )
  LET ALT.AVE.NUMBER.UPDATES(J) = AVE.NUMBER.UPDATES(J) *
    ( 1 / ( LINKS - 1 ))
LOOP
..
..      PRINT PKT STATISTICS
..
IF SPECIFY.OUTPUT = 0
..
  BEGIN REPCRT ON A NEW PAGE
  PRINT 1 LINE WITH TIME.ELAPSED AS FOLLOWS
  TIME ELAPSED IS ***** SEC.
  SKIP 1 OUTPUT LINE
..
  PRINT 1 LINE WITH NUMBER.CYCLES.COMPLETED AS FOLLOWS
  NUMBER OF CYCLES COMPLETED IS *****
  SKIP 1 OUTPUT LINE
..
  PRINT 2 LINES AS FOLLOWS
  NO.      MEAN TIME      PEAK TIME      IDEAL
  HOPPED   PKTS      PER PKT      TIME      TIME
  FOR I = 1 TO ( 10 * N.NODE ), DO
    IF HOP.CCUNT(I,PACKET) NE 0 ( 1 * HOP.COUNT(I,PACKET))
      LET TCT.HOPS = TCT.HOPS + ( 1 * HOP.COUNT(I,PACKET))
      LET AVE.TIME = CLOCK.DATA(I,1) / REAL.F(HOP.COUNT(I,PACKET))
      LET IDEAL.TIME = I*PKT.XMN.TIME + (I-1)*PROCESSING.TIME
      PRINT 1 LINE WITH I, HCP.COUNT(I,PACKET), AVE.TIME,
        CLOCK.DATA(I,2) AND IDEAL.TIME AS FOLLOWS
        *****
        ** REGARDLESS **
        ** ***** **
  LOOP
..
..      PRINT ALERT MSG IF A PKT HOPPED MORE THAN TOTAL NUMBER OF NODES
..
IF MSG.HLT NE 0
..
  SKIP 2 OUTPUT LINES

```



```

PRINT 1 LINE AS FCLLCWS
===== NOTE AT LEAST 1 PACKET HOPPED MORE THAN THE TOTAL NUMBER OF NODES =
SKIP 2 OUTPUT LINES
REGARDLESS
..
IF DELIVERED NE 0
LET AVE.NODES.HOPPED = REAL.F(TOT.HOPS) / REAL.F(DELIVERED)
ELSE
SKIP 1 OUTPUT LINE
PRINT 1 LINE AS FOLLOWS
... NO PACKETS HAVE BEEN DELIVERED DURING THIS PART OF THE SIMULATION..
REGARDLESS
..
PRINT SELECTED STATISTICAL DATA
..
SKIP 3 OUTPUT LINES
PRINT 1 LINE WITH AVE.NODES.HOPPED AS FOLLOWS
MEAN NUMBER OF NODES HOPPED PER PACKET IS **.*
..
SKIP 1 OUTPUT LINE
PRINT 1 LINE WITH NEW.MSG.TOTAL AND TOT.PACKETS AS FOLLOWS
A TOTAL OF *** NEW XMNS WERE STARTED (TOTALING **** PACKETS ).
..
PRINT 1 LINE WITH (TOT.PACKETS - DELIVERED) AS FOLLOWS
OF THESE, *** PACKETS WERE UNDELIVERED WHEN THE TEST WAS ENDED.
..
SKIP 1 OUTPUT LINE
LET RATIO = REAL.F((NET.U.LINKS)/REAL.F(UP.STARTS))
PRINT 1 LINE WITH RATIO AS FOLLOWS
FOR EACH NEW UPDATE, AN AVERAGE OF *** LINKS WERE USED.
..
SKIP 1 OUTPUT LINE
PRINT 1 LINE WITH LONGEST.PATH AS FOLLOWS
LONGEST PATH TAKEN BY A PACKET WAS **** LINKS.
..
SKIP 2 OUTPUT LINES
PRINT 4 LINES AS CF
NODE      AVE NUMBER OF    NUMBER OF
          UPDATES PER     UPDATES
          DESTINATION PER ORIGINATED
          CYCLE            OR RELAYED
          PER LINK
..
SKIP 1 OUTPUT LINE
FOR J= 1 TO N.NODE, DO
PRINT 1 LINE WITH J, AVE.NUMBER.UPDATES(J), ALT.AVE.NUMBER.UPDATE(J)
U.TOTAL(J), PKTS.RELAYED(J) AS FOLLOWS
****.*
*****
LOOP

```



```

..
REGARDLESS
..
IF PEEK = 2
  LET DLVRD.AT.HALF = DELIVERED
  LET TOT.HALF.PACKETS = TOT.PACKETS
REGARDLESS
..
IF PEEK = 4
  LET RATIO.STRANDED = REAL.F(( TOT.PACKETS - TOT.HALF.PACKETS ) -
    ( DELIVERED - DLVRD.AT.HALF )) / REAL.F( DELIVERED
    - DLVRD.AT.HALF )
REGARDLESS
..
IF PEEK = 2 CR PEEK = 4
..
  CALCULATE DIRECTIONAL FLOW OF PACKETS AND UPDATES IN EACH LINK.
  P.FLOW1 IS % TIME LINK IS BUSY PASSING PACKETS IN ONE DIRECTION
  P.FLOW2 IS % TIME LINK IS BUSY PASSING PACKETS IN OTHER DIRECTION
  ( SIMILARLY FOR U.FLOW1 AND U.FLOW2 )
..
PERFORM FLOW.ANC.DELAY
REGARDLESS
..
END **OF BEGIN REPORT
..
IF SPECIFY.OUTPUT = 0
..
  PRINT MAX UPDATE AND PACKET QUEUE LENGTHS
  AT THE END OF EACH QUARTER
..
  IF PRINT >= 0
    BEGIN REPORT ON A NEW PAGE
    PRINT 2 LINES AS FOLLOWS
    MAXIMUM QUEUE LENGTHS:
    FROM TO PACKET QUEUE MAX UPDATE QUEUE MAX
    FOR I = 1 TO LINKS, DO
      LET A = LINK.ABLE(I,1)
      LET B = LINK.ABLE(I,2)
      PRINT 1 LINE WITH A, B, LINK.MONITOR(A,B,3), LINK.MONITOR(A,B,5)
      AS FOLLOWS
      ***
      PRINT 1 LINE WITH B, A, LINK.MONITOR(B,A,3), LINK.MONITOR(B,A,5)
      AS FOLLOWS
      ***
      LOC
      ***
    END **OF BEGIN REPORT
  ..

```





```

** REGARDLESS
REGARDLESS
**
** PRINT THE QUEUE SIZES FROM 0 TO 500 AND THE NUMBER
** OF TIMES THE UPDATE OR PACKET OUTGOING QUEUES
** WERE FOUND TO BE OF THAT SIZE WHEN SAMPLED
** ( IE. QUEUE SIZE SAMPLE DENSITY ).
**
IF SPECIFY OUTPUT = 0
IF PRINT >= 0
  IF PEEK >= 3
    **
    BEGIN REPRCT ON A NEW PAGE
    PRINT 3 LINES WITH SMP.LINKS AND SMP.CNTR AS FOLLOWS
    OUTGICNG PACKET / UPDATE QUEUE DISTRIBUTION
    ** LINKS WERE SAMPLED
    ** SAMPLES PER LINK WERE TAKEN
    SKIP 2 OUTPUT LINES
    PRINT 2 LINES AS FOLLOWS
    PACKET QUEUE UPDATE QUEUE
    SAMPLE DENSITY SAMPLE DENSITY
    FOR I = 1 TO 1000 DO
      LET P.SUM = (I-1) * PKT.QU.DISTR(I) + P.SUM
      LET U.SUM = (I-1) * UP.QU.DISTR(I) + U.SUM
      LET P.X = P.X + UP.QU.DISTR(I)
      LET U.X = U.X + UP.QU.DISTR(I)
      LET P.Z2 = UP.QU.DISTR(I) * ((I-1)**2)
      LET U.Z2 = UP.QU.DISTR(I) * ((I-1)**2)
      LET P.Z2SUM = P.Z2SUM + P.Z2
      LET U.Z2SUM = U.Z2SUM + U.Z2
      IF PKT.QU.DISTR(I) NE 0 OR UP.QU.DISTR(I) NE 0
        IF PRINT 1 LINE WITH (I-1), PKT.QU.DISTR(I) AND
          UP.QU.DISTR(I) AS FOLLOWS
          **
          REGARDLESS
          LOOP
          LET P.Y = P.SUM / P.X
          LET U.Y = U.SUM / U.X
          SKIP 1 OUTPUT LINE
          PRINT 2 LINES WITH P.Y AND U.Y AS FOLLOWS
          **
          AVE PACKET QUEUE LENGTH = **
          AVE UPDATE QUEUE LENGTH = **
          LET P.XR = P.X
          LET U.XR = U.X
          LET P.SD = SQRT.F(( P.Z2SUM - P.XR * (P.Y**2) ) / ( P.XR-1. ))
          LET U.SD = SQRT.F(( U.Z2SUM - U.XR * (U.Y**2) ) / ( U.XR-1. ))
          SKIP 1 OUTPUT LINE

```



```

PRINT 2 LINES WITH P.SD AND U.SD AS FOLLOWS
PACKET QUEUE STANDARD DEVIATION = **.*****
UPDATE QUEUE STANDARD DEVIATION = **.*****
** CHECK ALL UNDELIVERED PKTS. REPORT ANY WITH A HOP COUNT > N.NODE
**
PRINT 1 LINE AS FOLLOWS
UNUSUAL DELAYS FOR PACKETS NOT DELIVERED DESCRIBED BELOW
FOR NO.DE = 1 TO N.NODE, DO
  FOR EACH MESSAGE IN PACKET.OUT.QUEUE(NO.DE) WITH TYPE(MESSAGE)
    = PACKET, DO
      IF NODES.HOPPED(MESSAGE) >= N.NCDE
        PRINT 1 LINE WITH RELEASE.TIME(MESSAGE),
          NODES.HOPPED(MESSAGE) AS FOLLOWS
        PACKET RELEASED AT ***.***** MAKES *** HOPS
        REGARDLESS
      LOOP
    LOOP
  **
  ** END ** OF BEGIN REPORT
  REGARDLESS
  REGARDLESS
  REGARDLESS
  IF PEEK NE 4
    ** SCHEDULE A REPORT.RESULTS IN ( TIME.LIMIT / 4. ) UNITS
    ELSE
      PERFORM SPECIAL.CUTPUT
      PERFORM DESTRUCTION
    **
    REGARDLESS
    **
    RETURN
  END ** OF REPCRT.RESULTS
  **
  ** THIS SUBROUTINE CALCULATES THE NETWORK FLOW AND
  ** THE AVERAGE DELAY PER PACKET
  **
  ROUTINE FOR FLOW.AND.DELAY
  **
  DEFINE T.DELAY1, T.DELAY2 AND GAMMA.INVERSE AS REAL VARIABLES
  DEFINE INSTANCE AND NEW.INSTANCE AS VARIABLE

```







```

IF PEEK = 4
..
SKIP 2 OUTPUT LINES
PRINT 3 LINES AS FOLLOWS
-- UTILIZATION FACTOR --
LINK      PACKET  UPDATE  TOTAL      PKTS IN  PKTS IN  WAIT TIME
..                                     QUEUE AT  QUEUE AT  FOR PKTS
..                                     HALF      END
..
.. SKIP 1 OUTPUT LINE
..
.. FOR I = 1 TO LINKS, DO
..
..   LET A = LINK.ABLE(I,1)
..   LET B = LINK.ABLE(I,2)
..
..   LET P.FLOW1 = (LINK.TIMER(1, A, B, 3) - LINK.TIMER(1, A, B, 4))
..               / (TIME.ELAPSED - (TIME.LIMIT * 0.5))
..   LET P.FLOW2 = (LINK.TIMER(1, B, A, 3) - LINK.TIMER(1, B, A, 4))
..               / (LINK.TIMER(1, B, A, 3) - LINK.TIMER(1, B, A, 4))
..   LET P.FLOW.TOTAL = P.FLOW1 + P.FLOW2 + P.FLOW.TOTAL
..
..   LET U.FLOW1 = (LINK.TIMER(2, A, B, 3) - LINK.TIMER(2, A, B, 4))
..               / (TIME.ELAPSED - (TIME.LIMIT * 0.5))
..   LET U.FLOW2 = (LINK.TIMER(2, B, A, 3) - LINK.TIMER(2, B, A, 4))
..               / (LINK.TIMER(2, B, A, 3) - LINK.TIMER(2, B, A, 4))
..   LET U.FLOW.TOTAL = U.FLOW1 + U.FLOW2 + U.FLOW.TOTAL
..
.. DEFINE N AS A REAL VARIABLE
..
.. LET T.DELAY1 = ( ( P.FLOW1**2 / (1.0 - U.FLOW1) ) / ( 1.0 -
..   U.FLOW1 - P.FLOW1 ) ) + P.FLOW1
.. LET T.DELAY2 = ( ( P.FLOW2**2 / (1.0 - U.FLOW2) ) / ( 1.0 -
..   U.FLOW2 - P.FLOW2 ) ) + P.FLOW2
..
.. LET TOTAL.DELAY = TOTAL.DELAY + T.DELAY1 + T.DELAY2
..
.. LET LINK1.FLOW = P.FLOW1 + U.FLOW1
.. LET LINK2.FLOW = P.FLOW2 + U.FLOW2
..
.. LET K = 1
.. FOR N = 0.0 TO 1.0 BY 0.1, DO
..   IF LINK1.FLOW > N AND LINK1.FLOW <= ( N + 0.1 )
..     LET HISTOGRAM (K) = HISTOGRAM (K) + 1
..   REGARDLESS
..   IF LINK2.FLOW > N AND LINK2.FLOW <= ( N + 0.1 )
..     LET HISTOGRAM (K) = HISTOGRAM (K) + 1
..   REGARDLESS
..
..

```





```

    LET K = K + 1
    LOCP
    PRINT 1 LINE WITH LINK.ABLE (I,1), LINK.ABLE (I,2), P.FLOW1, U.FLOW1,
    LINK1.FLOW, LINK.MCNITOR(A,B,6), LINK.MCNITOR(A,B,2)
    AND T.DELAY1 AS FOLLOWS
    ***
    PRINT 1 LINE WITH LINK.ABLE (I,2), LINK.ABLE (I,1), P.FLOW2, U.FLOW2,
    LINK2.FLOW, LINK.MCNITOR(B,A,6), LINK.MCNITOR(B,A,2)
    AND T.DELAY2 AS FOLLOWS
    ***
    ***
    LET PKTS.END = PKTS.END + LINK.MCNITOR(A,B,2)
    + LINK.MCNITOR(B,A,2)
    LCCP
    LET GAMMA.INVERSE = 1.0 / PKTS.PER.SEC.AVE
    LET AVE.DELAY.PER.PKT = GAMMA.INVERSE * TOTAL.DELAY
    LET AVE.P.FLOW = P.FLOW.TOTAL / ( 2 * LINKS )
    LET AVE.U.FLOW = U.FLOW.TOTAL / ( 2 * LINKS )
    LET AVE.NETWORK.FLOW = AVE.P.FLOW + AVE.U.FLOW
    FOR EACH NCDE, CC
    FOR EACH INSTANCE IN PACKET.OUT.QUEUE(NODE), DO
    LET STRANDED.WAIT = STRANDED.WAIT + TIME.V
    LET QUEUE.ENTRY.TIME(INSTANCE)
    LOOP
    T.IN.LINK REPRESENTS THE TOTAL TIME ALL PACKETS WHICH ARE
    NOT IN A QUEUE AND HAVE NOT BEEN DELIVERED BY THE END OF THE
    HAVE BEEN IN THE CURRENT LINK.
    Q.IN.LINK REPRESENTS THE TOTAL TIME PACKETS WHICH ARE IN
    QUEUE AT THE END OF THE SIMULATION HAVE BEEN IN QUEUE.
    FOR EACH NEW.INSTANCE IN LNK.FLAG(NODE), DO
    LET T.IN.LINK = T.IN.LINK + TIME.V - LINK.ENTRY.TIME(NEW.INSTANCE)
    LET Q.IN.LINK = Q.IN.LINK + TOT.QUEUE.TIME(NEW.INSTANCE)
    LOOP
    LCCP
    REGARDLESS
    RETURN
    END OF FLOW.AND.DELAY

```



```

.. THIS SUBROUTINE CCNTAINS THE SPECIAL OUTPUT FORMAT SPECIFIED
.. BY THE PROGRAMMER. THE SUBROUTINE IS ONLY EXECUTED
.. WHEN THE SIMULATION HAS COMPLETED ALL FOUR QUARTERS
.. OF ITS RUN AND SPECIFY.OUTPUT = 1.
..
ROUTINE FOR SPECIAL.OUTPUT
..
DEFINE N AND CHECK.DELAY AS A REAL VARIABLES
..
SKIP 1 OUTPUT LINE
PRINT 3 LINES WITH AVE.P.FLOW, AVE.U.FLOW AND AVE.NETWORK.FLOW
AS FOLLOWS
AVE.P.FLOW = **.*
AVE.U.FLOW = **.*
AVE.NETWORK.FLOW = **.*
..
LET CHECK.DELAY = (TRANSIT.TIME + STRANDED.WAIT + T.IN.LINK +
Q.IN.LINK) / REAL.F(GEN.COUNT)
PRINT 4 LINES WITH GEN.CCUNT, DEST.CCUNT, TRANSIT.TIME,
STRANDED.WAIT AS FOLLOWS
GEN.CCUNT = **.*
DEST.CCUNT = **.*
TRANSIT.TIME = **.*
STRANDED.WAIT = **.*
PRINT 3 LINES WITH T.IN.LINK AND Q.IN.LINK AND CHECK.DELAY AS FOLLOWS
T.IN.LINK = **.*
Q.IN.LINK = **.*
CHECK.DELAY = **.*
..
PRINT 2 LINES WITH AVE.DELAY.PER.PKT AND
RATIO.STRANDED AS FOLLOWS
AVE.DELAY.PER.PKT = **.*
RATIO.STRANDED = **.*
..
PRINT 2 LINES WITH PKTS.HALF AND PKTS.END
AS FOLLOWS
PKTS IN QUEUE AT HALF = **.*
PKTS IN QUEUE AT END = **.*
..
SKIP 1 OUTPUT LINE
PRINT 1 LINE AS FOLLOWS
INTERVAL NUMBER CF LINKS
..
LET N = 0.0
FOR I = 1 TO 10, DO
PRINT 1 LINE WITH N, ( N + .1 ) AND HISTOGRAM( I )
AS FOLLOWS
**.*
**.*

```



```

.. LET N = N + .1
.. LOOP
..
.. THE FOLLOWING STATEMENTS CAUSE THE RESULTS OF THE
.. SIMULATION TO BE WRITTEN TO THE MASS STORAGE
.. SYSTEM FOR LATER RETRIEVAL BY A PLOTTING
.. ROUTINE.
..
USE UNIT 8 FOR OUTPUT
WRITE PKTS.PER.SEC.AVE/NCDE.FACTOR, AVE.NETWORK.FLOW,
AVE.P.FLOW, AVE.U.FLOW, AVE.DELAY.PER.PKT, CHECK.DELAY AS
/D(6,2), S 1, D(9,6), S 1, D(9,6), S 1, D(9,6), S 1,
D(9,6)
USE UNIT 6 FOR OUTPUT
..
RETURN
END .. OF SPECIAL.CUTPUT
..
.. THE FOLLOWING SUBROUTINE CANCELS AND/OR DESTROYS ALL ENTITIES
.. AND EVENTS WHICH REMAIN IN THE TIMING ROUTINE AFTER
.. TIME.V = TIME.LIMIT. SINCE THIS ACTION EMPTIES THE
.. TIMING ROUTINE, CONTROL OF THE PROGRAM IS RETURNED TO THE
.. STATEMENT FOLLOWING *START SIMULATION* IN THE "MAIN"
.. ROUTINE FOR DESTRUCTION
..
DEFINE OCCURANCE AS VARIABLE
..
FOR EACH QU.SAMPLER IN EV.S(I.QU.SAMPLER), DO
  CANCEL THE QU.SAMPLER
  DESTROY THE QU.SAMPLER
.. LOOP
FOR EACH SAMPLE IN EV.S(I.SAMPLE), DC
  CANCEL THE SAMPLE
  DESTROY THE SAMPLE
.. LOOP
FOR EACH COMPUTE.CV IN EV.S(I.COMPUTE.CV), DO
  CANCEL THE COMPUTE.CV
  DESTROY THE COMPUTE.CV
.. LOOP
FOR EACH ADOPT.NEW.BEST.PATH IN EV.S(I.ADOPT.NEW.BEST.PATH), DO
  CANCEL THE ADOPT.NEW.BEST.PATH
  DESTROY THE ADOPT.NEW.BEST.PATH
.. LOOP
FOR EACH NEW.UPDATE.MESSAGE IN EV.S(I.NEW.UPDATE.MESSAGE), DO
  CANCEL THE NEW.UPDATE.MESSAGE

```



```

        DESTROY THE NEW.UPDATE.MESSAGE
    LOOP
    FOR EACH UPDATE.ARRIVES IN EV.S(I.UPDATE.ARRIVES), DO
        CANCEL THE UPDATE.ARRIVES
        DESTROY THE UPDATE.ARRIVES
    LOOP
    FOR EACH CONT.UPDATE.MESSAGE IN EV.S(I.CONT.UPDATE.MESSAGE), DO
        CANCEL THE CONT.UPDATE.MESSAGE
        DESTROY THE CONT.UPDATE.MESSAGE
    LOOP
    FOR EACH PACKET.ARRIVES IN EV.S(I.PACKET.ARRIVES), DO
        CANCEL THE PACKET.ARRIVES
        DESTROY THE PACKET.ARRIVES
    LOOP
    FOR EACH CON.PACKET.MESSAGE IN EV.S(I.CON.PACKET.MESSAGE), DO
        CANCEL THE CON.PACKET.MESSAGE
        DESTROY THE CON.PACKET.MESSAGE
    LOOP
    FOR EACH NEW.PACKET.MESSAGE IN EV.S(I.NEW.PACKET.MESSAGE), DO
        CANCEL THE NEW.PACKET.MESSAGE
        DESTROY THE NEW.PACKET.MESSAGE
    LOOP
    FOR EACH COMPLETED.TRIP IN EV.S(I.COMPLETED.TRIP), DO
        CANCEL THE COMPLETED.TRIP
        DESTROY THE COMPLETED.TRIP
    LOOP
    FOR EACH NOCE, DO
        FOR EACH CCCURANCE CF UPDATE.OUT.QUEUE, DO
            REMOVE CCCURANCE FROM UPDATE.OUT.QUEUE
            DESTROY MESSAGE CALLED CCCURANCE
        LOOP
        FOR EACH CCCURANCE OF PACKET.OUT.QUEUE, DO
            REMOVE CCCURANCE FROM PACKET.OUT.QUEUE
            DESTROY MESSAGE CALLED CCCURANCE
        LOOP
        FOR EACH CCCURANCE OF LINK.FLAG, DO
            REMOVE CCCURANCE FROM LINK.FLAG
            DESTROY MESSAGE CALLED CCCURANCE
        LOOP
        FOR EACH CCCURANCE CF TIME.QUEUE, DO
            REMOVE CCCURANCE FROM TIME.QUEUE
            DESTROY PACK CALLED CCCURANCE
        LOOP
    LOOP

```





```

RETURN
END ** OF DESTRUCTION
**
** THIS ROUTINE IS CALLED WHEN A NCDE ORIGINATES AN UPDATE MESSAGE.
** THE INITIAL U-MSG IS SENT TO ALL OF THE INITIATING NODE'S NEIGHBORS
**
EVENT NEW.UPDATE.MESSAGE GIVEN SENDING.NCDE AND TYPE.MESSAGE
LET UP.STARTS = UP.STARTS + 1
FOR I = 1 TO LINKS, DO
**
** CHECK EACH LINK TO SEE IF SENDING.NCDE IS ON ONE END
**
IF (LINK.ABLE(I,1) = SENDING.NODE OR LINK.ABLE(I,2) = SENDING.NODE)
  CREATE A MESSAGE
  LET TYPE(MESSAGE) = UPDATE
  LET RELAYER(MESSAGE) = SENDING.NCDE
  LET U.TOTAL(SENDING.NODE) = U.TOTAL(SENDING.NODE) + 1
  IF LINK.ABLE(I,1) = SENDING.NODE
**
** IF OPPOSITE NCDE IS IN ANOTHER FAMILY:
**
IF FAMILY (LINK.ABLE(I,2)) NE FAMILY (SENDING.NODE)
  LET FAM.LY (MESSAGE) = FAMILY (SENDING.NODE)
  LET DESTINATION(MESSAGE) = FAMILY (SENDING.NODE)
  GO LIST.NEXT.STOP
  ELSE
**
** IF OPPOSITE NODE IS IN ANOTHER GROUP (SAME FAMILY):
**
IF GROUP (LINK.ABLE(I,2)) NE GROUP (SENDING.NODE)
  LET GRP (MESSAGE) = GROUP (SENDING.NODE)
  LET DESTINATION (MESSAGE) = GROUP (SENDING.NODE)
  GO LIST.NEXT.STOP
  ELSE
**
** IF OPPOSITE NCDE IS IN SAME BASIC GROUP
**
IF OPPOSITE NCDE IS IN SAME BASIC GROUP
  LET DESTINATION(MESSAGE) = LINK.ABLE(I,1)
  LIST.NEXT.STOP:
  LET NEXT.STOP(MESSAGE) = LINK.ABLE(I,2)
  ELSE
  IF FAMILY (LINK.ABLE(I,1)) NE FAMILY (SENDING.NODE)
    LET FAM.LY (MESSAGE) = FAMILY (SENDING.NODE)
    LET DESTINATION (MESSAGE) = FAMILY (SENDING.NODE)
    GO INCL.NEXT.STOP
  ELSE
    IF GROUP (LINK.ABLE(I,1)) NE GROUP (SENDING.NODE)

```



```

LET GRP (MESSAGE) = GROUP (SENDING.NODE)
LET DESTINATION (MESSAGE) = GROUP (SENDING.NODE)
GO INCL.NEXT.STOP
ELSE
LET DESTINATION(MESSAGE) = LINK.ABLE(I,2)
'INCL.NEXT.STOP,
LET NEXT.STOP (MESSAGE) = LINK.ABLE(I,1)
REGARDLESS
IF PRNT >= 4
SKIP 1 OUTPUT LINE
PRINT 1 LINE WITH SENDING.NODE, NEXT.STOP(MESSAGE),
DESTINATION(MESSAGE) AND TIME.V AS FOLLOWS
UPDATE ORIGINATED BY *** TO *** FOR DESTINATION *** AT ****.***** SEC
REGARDLESS
..
.. IF LINK TO NEIGHBCR IS IDLE, SEND OUT UPDATE
..
.. IF LINK.MONITOR( RELAYER(MESSAGE), NEXT.STOP(MESSAGE), 1 ) = IDLE
..
.. SCHEDULE ARRIVAL CF UPDATE AT OPPOSITE NCDE
..
.. SCHEDULE AN UPDATE.ARRIVES GIVEN MESSAGE IN
.. U.XMN.TIME UNITS
.. LET LINK.TIMER( 2, RELAYER(MESSAGE), NEXT.STOP(MESSAGE), 1 )
.. = TIME.V
.. LET LINK.MONITOR( RELAYER(MESSAGE), NEXT.STOP(MESSAGE), 1 ) = BUSY
..
.. IF PRNT >= 4
.. SKIP 1 OUTPUT LINE
.. PRINT 2 LINES WITH SENDING.NCDE AND U.TOTAL(SENDING.NODE)
.. AS FOLLOWS
.. UPDATE DOES NOT WAIT IN QUEUE.
.. NODE *** HAS PASSED CR ORIGINATED ***** UPDATES
.. REGARDLESS
..
.. IF PRNT >= 5
.. SKIP 1 OUTPUT LINE
.. PRINT 1 LINE WITH RELAYER(MESSAGE), NEXT.STOP(MESSAGE) AND
.. TIME.V AS FOLLOWS
.. LINK *** / *** BUSY TRANSMITTING UPDATE AT ****.***** SEC.
.. REGARDLESS
..
.. ELSE
.. IF THE LINK IS BUSY, STCRE UPDATE AT THE END OF THE OUTGOING
.. UPDATE QUEUE FCR THAT LINK
.. FILF MESSAGE IN UPDATE.OUT.QUEUE( RELAYER(MESSAGE) )

```









```

..
..
..
IF LINK.MONITOR(RELAYER(MESSAGE), NEXT.STOP(MESSAGE), 1) = IDLE
..
..
..
SCHEDULE THE RELAYED UPDATE TO ARRIVE AT THE NEXT DESTINATION
..
..
..
SCHEDULE AN UPDATE.ARRIVES GIVEN MESSAGE IN U.XMN.TIME UNITS
LET LINK.TIMER(2, RELAYER(MESSAGE), NEXT.STOP(MESSAGE), 1)
= TIME.V
LET LINK.MONITOR(RELAYER(MESSAGE), NEXT.STOP(MESSAGE), 1)
= BUSY
..
..
..
IF PRNT >= 4
SKIP 1 OUTPUT LINE
PRINT 3 LINES WITH RELAYER(MESSAGE), NEXT.STOP(MESSAGE),
DESTINATION(MESSAGE), TIME.V, LAST.NODE AND
U.TOTAL(LAST.NODE) AS FOLLOWS
UPDATE RELAYED FROM *** TO *** FOR DESTINATION *** AT ***.***** SEC
RELAYED UPDATE DOES NOT WAIT IN OUTGOING UPDATE QUEUE
NODE *** HAS PASSED *****
REGARDLESS
..
..
..
IF PRNT >= 5
SKIP 1 OUTPUT LINE
PRINT 1 LINE WITH RELAYER(MESSAGE), NEXT.STOP(MESSAGE) AND
TIME.V AS FOLLOWS
LINK *** / *** BUSY TRANSMITTING UPDATE AT ***.***** SEC.
REGARDLESS
..
..
..
ELSE
..
..
..
IF LINK IS BUSY, STORE THE UPDATE AT THE END OF THE OUTGOING UPDATE
QUEUE FOR THAT LINK
..
..
..
FILE MESSAGE IN UPDATE.OUTPUT.QUEUE(RELAYER(MESSAGE), 4) = 1
LET LINK.MONITOR(RELAYER(MESSAGE), NEXT.STOP(MESSAGE), 4) + 1
LINK.MONITOR(RELAYER(MESSAGE), NEXT.STOP(MESSAGE), 4) > 1
IF LINK.MONITOR(RELAYER(MESSAGE), NEXT.STOP(MESSAGE), 5) =
LET LINK.MONITOR(RELAYER(MESSAGE), NEXT.STOP(MESSAGE), 5) =
LINK.MONITOR(RELAYER(MESSAGE), NEXT.STOP(MESSAGE), 4)
REGARDLESS
..
..
..
IF PRNT >= 4
SKIP 1 OUTPUT LINE
PRINT 3 LINES WITH RELAYER(MESSAGE), NEXT.STOP(MESSAGE),
DESTINATION(MESSAGE), TIME.V, RELAYER(MESSAGE) AND
LINK.MONITOR(RELAYER(MESSAGE), NEXT.STOP(MESSAGE), 4)
AS FOLLOWS
UPDATE FROM NODE *** TO *** WITH DESTINATION NODE *** ENTERS

```





```

OUTGOING UPDATE QUEUE AT ***** SEC
OUTGOING UPDATE QUEUE FROM NODE **** IS *****
REGARDCLESS

.. REGARDLESS
..
RETURN
END ..CF CONT.UPDATE.MESSAGE
..
.. THIS ROUTINE PROCESSES AN UPDATE MESSAGE AS IT ARRIVES IN A NODE,
.. RELAYING IT TO NEIGHBORS IF APPROPRIATE
..
EVENT UPDATE.ARRIVES GIVEN ID.MESSAGE.NUMBER
..
DEFINE RELAY.NODE AND MSG.NR AS VARIABLES
..
LET MSG.NR = ID.MESSAGE.NUMBER
..
LET LINK.TIMER( 2, RELAYER(MSG.NR), NEXT.STOP(MSG.NR), 2 ) = TIME.V
LET LINK.TIMER( 2, RELAYER(MSG.NR), NEXT.STOP(MSG.NR), 3 ) = +
LINK.TIMER( 2, RELAYER(MSG.NR), NEXT.STOP(MSG.NR), 3 ) -
LINK.TIMER( 2, RELAYER(MSG.NR), NEXT.STOP(MSG.NR), 2 ) -
LINK.TIMER( 2, RELAYER(MSG.NR), NEXT.STOP(MSG.NR), 1 )

.. THIS.NODE = NEXT.STOP(MSG.NR)
LET THIS.NODE = NEXT.STOP(MSG.NR)
LET NET.U.LINKS = NET.U.LINKS + 1
LET NET.NODES.HOPPED(MSG.NR) = NCDES.HOPPED(MSG.NR) + 1
..
IF PRNT >= 4
  SKIP 1 OUTPUT LINE
  PRINT 1 LINE WITH NEXT.STOP(MSG.NR), RELAYER(MSG.NR),
  DESTINATION(MSG.NR) AND TIME.V AS FOLLOWS
  UPDATE ARRIVES AT *** FROM *** FOR DESTINATION *** AT ****.***** SEC.
  REGARDLESS
..
.. ID CV OF LAST RELAYING NODE
..
FOR I = 1 TO MAX.LINKS.PER.NCDE, DO
  IF NEIGHBOR.LIST(THIS.NODE, I, 1) = RELAYER(MSG.NR)
    LET CV.OF.LINK = NEIGHBOR.LIST( THIS.NODE, I, 3 )
    GO SELECT.BEST.PATH
  ELSE
    LOOP
  SELECT.BEST.PATH
  LET TOTAL.CV.OF.PATH = CV.OF.LINK + CHANNEL.VALUE(MSG.NR)
..
.. ID PREVIOUSLY SELECTED BP NEIGHBOR

```



```

..
LET BP.NEIGHBOR = BEST.PATH(THIS.NODE, DESTINATION(MSG.NR), 3)
..
IF RELAYER = CURRENT BP NEIGHBOR, UPDATE ITS CV TO THE DESTINATION
.. AND RELAY UPDATE
..
IF RELAYER(MSG.NR) = BP.NEIGHBOR
.. LET BEST.PATH(THIS.NODE, DESTINATION(MSG.NR), 4) = CHANNEL.VALUE(MSG.NR)
..
IF PRNT >= 3
SKIP 1 OUTPUT LINE
PRINT 2 LINES WITH THIS.NODE, DESTINATION(MSG.NR), BP.NEIGHBOR,
TIME.V, CHANNEL.VALUE(MSG.NR), CV.OF.LINK AND TOTAL.CV.OF.PATH
AS FOLLOWS
NODE *** UPDATES CV THRU SAME BP TO *** (THRU *** AT ***.***** SEC
CV = *** + *** = ***
SKIP 1 OUTPUT LINE
REGARDLESS
.. GO RELAY.UPDATE.TO.NEIGHBORS
ELSE
..
.. IF THERE WAS NO BP NEIGHBOR, ADAPT RELAYER AS BP NEIGHBOR AND
.. RELAY UPDATE
..
IF BP.NEIGHBOR = NCNE
LET BEST.PATH(THIS.NCDE, DESTINATION(MSG.NR), 3) = RELAYER(MSG.NR)
LET BEST.PATH(THIS.NCDE, DESTINATION(MSG.NR), 4) = CHANNEL.VALUE(MSG.NR)
LET BP.NEIGHBOR = RELAYER(MSG.NR)
..
.. IF PRNT >= 3
SKIP 1 OUTPUT LINE
PRINT 2 LINES WITH THIS.NCDE, DESTINATION(MSG.NR), BP.NEIGHBOR,
TIME.V AND TOTAL.CV.OF.PATH AS FOLLOWS
NEW BEST PATH FROM *** TO *** NOW THRU *** AT ***.***** SEC.
SKIP 1 OUTPUT LINE
REGARDLESS
.. GO RELAY.UPDATE.TO.NEIGHBORS
ELSE
..
.. IF THE RELAYER IS NOT THE BP NEIGHBOR, AND IF THE NEW PATH IS
.. SHORTER THAN THE OLD BEST PATH, MAKE RELAYER THE NEW BP NEIGHBOR
.. AND RELAY THE UPDATE
..
FOR I = 1 TO MAX.LINKS.PER.NCDE, DO
IF NEIGHBCR.LIST(THIS.NODE, I, 1) = BP.NEIGHBOR

```



```

LET CV.TC.BP.NEIGHBOR = NEIGHBOR.LIST(THIS.NODE,1,3)
GO COMPARE.CVS
ELSE
LOOP
'COMPARE.CVS'
IF (BEST.PATH(THIS.NODE, DESTINATION(MSG.NR),4) + CV.TO.BP.NEIGHBOR) >
TOTAL.CV.GF.PATH
LET OLD.BP = BP.NEIGHBOR
LET LNK.CV = CV.TO.BP.NEIGHBOR
LET BEST.PATH(THIS.NODE, DESTINATION(MSG.NR), 3) = RELAYER(MSG.NR)
LET BEST.PATH(THIS.NODE, DESTINATION(MSG.NR), 4) = CHANNEL.VALUE
(MSG.NR)
LET BP.NEIGHBOR = RELAYER(MSG.NR)
..
IF PRNT >= 2
SKIP 1 OUTPUT LINE
PRINT 2 LINES WITH THIS.NCDE, DESTINATION(MSG.NR), BP.NEIGHBOR,
TIME.V, CHANNEL.VALUE(MSG.NR), CV.OF.LINK AND
TOTAL.CV.OF.PATH AS FCLLCWS
NEW BEST CV = *** + *** NOW THRU *** AT ****.***** SEC.
PRINT 1 LINE WITH OLD.BP, OLD.CV, LNK.CV, (OLD.CV + LNK.CV) AS FOLLOWS
SKIP 1 OLD BP THRU *** HAD CV OF *** + *** = ***
REGARDLESS
..
GO RELAY.UPDATE.TO.NEIGHBORS
ELSE
.. IF NEW PATH IS NOT BETTER THAN THE OLD BEST PATH, DISCONTINUE U-MSG
.. GO DISCONTINUE.ORIGINAL.MESSAGE
..
.. IF A NEW BP IS SELECTED OR AN OLD BP IS UPDATED, PREPARE INFORMATION
.. FOR THE NEXT U-MSG TO ALL NEIGHBORS
..
RELAY.UPDATE.TO.NEIGHBORS'
FOR I=1 TO MAX.LINKS.PER.NCDE, DO
IF NEIGHBOR.LIST(THIS.NODE, I, 1) = BP.NEIGHBOR
LET CV.TO.BP.NEIGHBOR = NEIGHBOR.LIST(THIS.NODE, I, 3)
GO COMPUTE.NET.CV
ELSE
LOOP
'COMPUTE.NET.CV'
LET NET.CV.FROM.THIS.NCDE = BEST.PATH(THIS.NODE, DESTINATION(MSG.NR),4)
+ CV.TO.BP.NEIGHBOR
FOR I=1 TO MAX.LINKS.PER.NCDE, DO
IF NEIGHBOR.LIST(THIS.NODE, I, 2) = YES

```



```

IF NEIGHBOR.LIST (THIS.NODE, I,1) NE RELAYER (MSG.NR)
LET UPSTREAM.NCDE = NEIGHBOR.LIST (THIS.NODE, I, 1)
IF UPSTREAM.NODE IS IN ANOTHER FAMILY AND THIS IS A INTRA-FAMILY
U-MSG, RELAY IT
IF (FAM.LY(MSG.NR) NE 0 AND FAMILY(UPSTREAM.NODE) NE FAM.LY(MSG.NR))
GO RETRANS.UPSTREAM
ELSE
IF UPSTREAM.NODE IS IN ANOTHER GROUP AND THIS IS A INTRA-GROUP (SAME
FAMILY) U-MSG, RELAY IT
IF (GRP(MSG.NR) NE 0 AND GROUP(UPSTREAM.NODE) NE GRP(MSG.NR))
GO RETRANS.UPSTREAM
ELSE
IF UPSTREAM.NODE IS IN THE SAME BASIC GROUP AND THIS IS A BASIC
GROUP ORIGINATED U-MSG, RELAY IT
IF (GROUP(UPSTREAM.NCDE) = GROUP(THIS.NODE)
AND FAM.LY(MSG.NR) = GRP(MSG.NR))
GO RETRANS.UPSTREAM
ELSE
IF NONE OF THE ABOVE, UPSTREAM.NODE DOES NOT GET A U-MSG
GO SKIP.PRINT
RETRANS.UPSTREAM.
LET HOPS = NODES.HOPPED(MSG.NR)
SCHEDULE A CONT.UPDATE.MESSAGE GIVEN THIS.NODE, UPSTREAM.NODE, HOPS,
NET.CV.FROM.THIS.NODE, DESTINATION(MSG.NR), FAM.LY(MSG.NR), HOPS,
AND GRP(MSG.NR) IN (PROCESSING.TIME * UP.PAC.RATIO) UNITS
SKIP.PRINT,
REGARDLESS
LOOP
IN THE SIMULATION, ALL U-MSGS ARE DESTROYED AFTER TRAVELING ONE
LINK. HOWEVER THE UPDATE CYCLE PROCEEDS ACCORDING TO THE BASIC
CONCEPT BECAUSE THE ARRIVING U-MSG CAUSES NEW U-MSGS TO BE
INITIATED IF A NEW BP WAS SELECTED OR AN OLD BP WAS UPDATED.
IF A NCDE COULD NOT USE AN INCMING U-MSG, IT IS DESTROYED
WITHOUT GENERATING ANY NEW U-MSGS.
DISCONTINUE.ORIGINAL.MESSAGE.
IF NCDES.HOPPED(MSG.NR) > MAX.U.HOPS
LET MAX.U.HOPS = NCDES.HOPPED(MSG.NR)

```





```

REGARDLESS
LET RELAY.NCDE = RELAYER(MSG.NR)
DESTROY MESSAGE CALLED MSG.NR
..
..
.. GO TO THE OUTGOING UPDATE QUEUE OF THE NODE WHICH RELAYED THE ABOVE
.. UPDATE, IF THE UPDATE QUEUE IS EMPTY, DEFINE THE LINK AS IDLE
.. AND CHECK THE NODE'S PACKET QUEUE FOR PACKETS TO BE RELAYED BY
.. DELIVERED TO THIS NODE. OTHERWISE, PLACE THE NEXT UPDATE ON
.. THE LINK AND ADJUST THE UPDATE QUEUE LENGTH
..
FOR EACH MESSAGE IN UPDATE.OUT.QUEUE( RELAY.NODE )
WITH NEXT.STOP(MESSAGE) = THIS.NODE
FIND THE FIRST CASE
IF NONE
..
.. CHECK PACKET QUEUE AT THE NODE WHICH SENT THIS UPDATE FOR PACKETS
.. TO BE RELAYED BY OR DELIVERED TO THIS NODE. IF PACKET QUEUE IS
.. EMPTY, DEFINE THE LINK AS IDLE; OTHERWISE, PLACE THE
.. NEXT PACKET FOR THIS NODE ON THE LINK
..
FOR EACH MESSAGE IN PACKET.OUT.QUEUE( RELAY.NODE )
WITH NEXT.STOP(MESSAGE) = THIS.NODE
FIND THE FIRST CASE
IF NONE
..
.. LET LINK.MCNITCR( RELAY.NODE, THIS.NODE, 1 ) = IDLE
..
IF PRNT >= 5
SKIP 1 OUTPUT LINE
PRINT 1 LINE WITH RELAY.NODE, THIS.NODE AND TIME.V AS FOLLOWS
LINK*** / *** IDLE AT ***.*** SEC.
REGARDLESS
..
..
ELSE REMOVE MESSAGE FROM PACKET.OUT.QUEUE( RELAY.NODE )
FILE MESSAGE IN LNK.FLAG(RELAY.NODE)
LET LINK.ENTRY.TIME(MESSAGE) = TIME.V
LET TOT.QUEUE.TIME(MESSAGE) = TOT.QUEUE.TIME(MESSAGE) + TIME.V
LET CUEUE.ENTRY.TIME(MESSAGE) = 0.0
..
.. SCHEDULE THE ARRIVAL OF THE PACKET JUST RELEASED FROM THE QUEUE
..
.. SCHEDULE A PACKET.ARRIVES GIVEN MESSAGE IN PKT.XMN.TIME UNITS
.. LET LINK.MONITCR( RELAY.NODE, THIS.NODE, 2 ) =
.. LINK.MCNITCR( RELAY.NODE, THIS.NODE, 1 ) - TIME.V
..
.. IF PRNT >= 1

```



```

SKIP 1 OUTPUT LINE
PRINT 3 LINES WITH INFO1(MESSAGE), INFO2(MESSAGE), RELAY.NODE,
THIS.NODE, DESTINATION(MESSAGE), TIME.V, RELAY.NODE AND
LINK.MCNITCR( RELAY.NODE, THIS.NODE, 2 ) AS FOLLOWS
RELEASED FROM THE OUTGOING PACKET QUEUE OF NODE ***
WITH DESTINATION *** AT ***.***.***.*** SEC.
OUTGOING PACKET QUEUE FROM NODE *** IS *****
REGARDLESS
" REGARDLESS
ELSE
REMOVE MESSAGE FROM UPDATE.OUT.QUEUE( RELAY.NODE )
"
" SCHEDULE ARRIVAL CF UPDATE JUST RELEASED FROM QUEUE
"
SCHEDULE AN UPDATE.ARRIVES GIVEN MESSAGE IN U.XMN.TIME UNITS
LET LINK.MONITOR( RELAY.NODE, THIS.NODE, 4 ) =
LINK.MCNITCR( RELAY.NODE, THIS.NODE, 4 ) - 1
LET LINK.TIMER( 2, RELAY.NODE, THIS.NODE, 1 ) = TIME.V
"
IF PRNT >= 4
SKIP 1 OUTPUT LINE
PRINT 3 LINES WITH RELAY.NODE, THIS.NODE, TIME.V, RELAY.NODE AND
LINK.MCNITCR( RELAY.NODE, THIS.NODE, 4 ) AS FOLLOWS
UPDATE RELEASED FROM THE OUTGOING UPDATE QUEUE OF NODE *** TO ***
AT ***.***.***.*** SEC.
OUTGOING UPDATE QUEUE FROM NODE *** IS *****
REGARDLESS
" REGARDLESS
" REGARDLESS
RETURN
END **OF UPDATE.ARRIVES
"
" THIS ROUTINE CALCULATES CHANNEL VALUES BASED ON A TIME-WEIGHTED
AVERAGE OF QUEUE SIZES OVER A SPECIFIED TIME CALLED THE WINDOW.
QUEUE SIZE INFORMATION OLDER THAN THE WINDOW TIME IS DISCARDED.
EVENT COMPUTE.CV
DEFINE EDGE.LAST, SUM, LAS.CU, SPAN, MIC, AREA, WEIGHT, BLOCK
AND REMAINDER AS REAL VARIABLES
DEFINE NONE TO MEAN 0
"
IF PRNT >= 2
SKIP 1 OUTPUT LINE
PRINT 2 LINES WITH TIME.V AS FOLLOWS
UPDATE CYCLE BEGINS AT ***.***.***.*** SEC

```



```

NEW CHANNEL VALUES ARE BEING COMPUTED
SKIP 1 OUTPUT LINE
REGARDLESS
..
FOR THIS.NODE = 1 TO N.NODE, DO
..
..    DESTROY QUEUE INFCRMATION BEYOND WINDOW SIZE.  "PACK" IS A PACKAGE
..    CF INFORMATION DESCRIBED LATER.
..
FOR EACH PACK IN TIME.QUEUE (THIS.NODE) WITH ENTRY.TIME(PACK) <
    (TIME.V - WINDOW), DO
        REMOVE PACK FROM TIME.QUEUE (THIS.NODE)
        DESTROY PACK
    LGCP
..
..    CALCULATE THE CV TO EACH NEIGHBOR
..
FOR J = 1 TO MAX.LINKS.PER.NODE, DO
    IF NEIGHBOR.LIST (THIS.NODE, J, 2) = YES
        LET NEIB = NEIGHBOR.LIST (THIS.NODE, J, 1)
        LET EDGE = C.O
        LET LAST = TIME.V
        LET SUM = 0.0
        LET LAS.QU = 0.0
        LET ANY.PACKS = NONE
        FOR EACH PACK IN TIME.QUEUE (THIS.NODE) WITH
            PAC.NEIGHBOR (PACK) = NEIB, DO
            LET ANY.PACKS = YES
            LET SPAN = LAST - ENTRY.TIME (PACK)
            LET MID = SPAN/2. + EDGE
            LET AREA = REAL.F(NUMBER(PACK)) * SPAN
            LET BLOCK = AREA
            LET SUM = SUM + BLOCK
            LET EDGE = EDGE + SPAN
            LET LAST = ENTRY.TIME(PACK)
            LET LAS.QU = REAL.F(NUMBER(PACK))
        LOOP
    IF ANY.PACKS = NCNE
        LET LAS.QU = LINK.MCNITOR (THIS.NODE, NEIB, 2)
    REGARDLESS
    LET REMAINDER = WINDOW - EDGE
    LET MID = (REMAINDER/2.) + EDGE
    LET AREA = LAS.QU * REMAINDER
    LET BLOCK = AREA
    LET SUM = SUM + BLOCK
    LET CV.OF.LINK = INT.F(SUM/WINDOW + 1.)
    LET NEIGHBOR.LIST (THIS.NODE, J, 3) = CV.OF.LINK
    REGARDLESS

```



```

LOOP
LOOP
..
.. SCHEDULE THE NEXT CV CALCULATION FOR ALL NEIGHBORS. IN THE
.. SIMULATION, THIS PROCESS IS SYNCHRONIZED FOR EVERY NODE IN
.. THE NETWORK.
..
.. SCHEDULE A ADPT.NEW.BEST.PATH IN (2*UP.DATE.PERIOD) UNITS
..
.. EARLIEST.UPDATE AND LATEST.UPDATE SET THE NEXT INTERVAL DURING
.. WHICH ALL NCDES WILL RANDOMLY INITIATE AN UPDATE MESSAGE. AFTER
.. THIS PERIOD THERE IS ANOTHER EQUAL LENGTH PERIOD WHICH ALLOWS ALL
.. UPDATE MESSAGES TO TRANSIT THE NETWORK AND REACH THEIR FINAL
.. "DESTINATIONS" BEFORE THE NEXT "COMPUTE.CV".
..
LET EARLIEST.UPDATE = TIME.V + (2* UP.DATE.PERIOD)
LET LATEST.UPDATE = TIME.V + (3* UP.DATE.PERIOD)
..
RETURN
END ..OF CCMPUTE.CV
..
.. THIS ROUTINE ESTABLISHES THE BEST PATHS TO BE USED FOR PACKET
.. TRANSMISSION DURING THE NEXT UPDATE CYCLE. BEST PATHS
.. ARE NOT CHANGED DURING THE UPDATE CYCLE.
..
EVENT ADPT.NEW.BEST.PATH
FOR I = 1 TC N.NODE, DO
FOR J = 1 TC NGFS, DO
LET BEST.PATH ( I, J, 1 ) = BEST.PATH ( I, J, 3 )
LET BEST.PATH ( I, J, 2 ) = BEST.PATH ( I, J, 4 )
LOOP
LOOP
..
.. THE COMPUTE.CV EVENT IS NOW CALLED. THIS ENSURES THAT
.. THE ORDER OF ADOPTING A NEW BEST PATH AND THEN COMPUTING
.. THE CHANNEL VALUES FOR THE NEXT UPDATE CYCLE IS PRESERVED
.. DURING THE EXECUTION OF THE SIMULATION.
..
SCHEDULE A CCMPUTE.CV NOW
..
RETURN
END ..OF ADCT.NEW.BEST.PATH
..
.. THIS ROUTINE GENERATES MESSAGES MADE UP OF A RANDOM
.. NUMBER OF PKTS (BETWEEN PRESCRIBED LIMITS). PKTS ARE SENT OUT
.. CN IDLE LINKS IF AVAILABLE, OR STORED IN QUEUES IF LINKS ARE BUSY.

```





```

.. EVENT NEW PACKET MESSAGE GIVEN I.MESSAG
DEFINE CK.XMTR, CK.RCVR, X.TCT.PERCENT AND R.TOT.PERCENT AS REAL
VARIABLES
LET X.TOT.PERCENT = 0
LET R.TOT.PERCENT = 0
LET CK.XMTR = UNIFORM.F(0.0, TRNS.PCNT, 2)
.. SELECTOR IS USED IF A PERCENTAGE OF THE MESSAGES ARE REQUIRED
.. TO BE BETWEEN NODES OF THE SAME GROUP OR FAMILY.
LET SELECTOR = UNIFORM.F(0.0, 100., 9)
.. SELECT THE TRANSMITTING NODE
..
FOR I = 1 TO N.NODE, DO
LET X.TOT.PERCENT = X.TOT.PERCENT + TRANSMIT.PERCENT(I)
IF CK.XMTR <= X.TOT.PERCENT
LET XMTR = I
GO FIND.RECEIVER
ELSE
LOOP
.. SELECT THE RECEIVER
..
IF FIND.RECEIVER,
LET CK.RCVR = UNIFORM.F(0.0, RCV.PCNT, 3)
FOR J = 1 TO N.NODE, DO
LET R.TOT.PERCENT = R.TOT.PERCENT + RECEIVE.PERCENT(J)
IF CK.RCVR <= R.TOT.PERCENT
LET RCVR = J
GO CK.GROUPS.AND.FAMILIES
ELSE
LOOP
.. IF THE RECEIVER MUST BE WITHIN THE SAME GROUP OR FAMILY, KEEP
.. LOOKING UNTIL AN ADEQUATE RECEIVER IS FOUND.
..
CK.GROUPS.AND.FAMILIES
IF SELECTOR < IN.GROUP
IF GROUP(XMTR) = GROUP(RCVR)
GO SEE.IF.XMTR.EQ.RCVR
ELSE
LET R.TCT.PERCENT = 0.0
GO FIND.RECEIVER
ELSE
SELECTOR < (IN.GROUP + IN.FAMILY)
IF FAMILY(XMTR) = FAMILY(RCVR)

```



```

GO SEE. IF XMTR.EQ.RCVR
ELSE
  LET R.TCI.PERCENT = 0.0
  GO FIND.RECEIVER
ELSE
  IF XMTR.EQ.RCVR
  'SEE RCVR = XMTR
  IF R.TOT.PERCENT = 0.0
  GO FIND.RECEIVER
ELSE
  'DERIVE NUMBER OF PACKETS'
  LET PKT.COUNT = INT.F(UNIFORM.F(1.0, MAX.PKTS.PER.MSG, 4))
  'COUNT TOTAL NUMBER OF MESSAGES GENERATED. THE 'TRACER' ARRAY KEEPS
  'TRACK OF THE TOTAL NUMBER OF PACKETS GENERATED.
  LET NEW.MSG.TOTAL = NEW.MSG.TOTAL + 1
  LET TRACER (NEW.MSG.TOTAL, 1) = PKT.COUNT
  'CREATE A MESSAGE FOR EACH PACKET
  FOR I = 1 TO PKT.COUNT, DO
    'CREATE A MESSAGE
    LET TYPE(MESSAGE) = PACKET
    LET RELAYER(MESSAGE) = XMTR
    LET FG = 0
    LET GEN.COUNT = GEN.COUNT + 1
    LET ORIG.TIME(MESSAGE) = TIME.V
    'ADDRESS PKT TC NODE, GROUP OR FAMILY OF DESTINATION AS APPROPRIATE
    IF FAMILY(XMTR) NE FAMILY(RCVR)
    LET BP.NODE = BEST.PATH (XMTR, FAMILY(RCVR), 1)
    LET FM.GP(MESSAGE) = FAMILY(RCVR)
    LET FG = FAMILY(RCVR)
    GO ADD.DESTINATION
  ELSE
    IF GROUP(XMTR) NE GROUP(RCVR)
    LET BP.NODE = BEST.PATH (XMTR, GROUP(RCVR), 1)
    LET FM.GP(MESSAGE) = GROUP (RCVR)
    LET FG = GROUP (RCVR)
    GO ADD.DESTINATION
  ELSE
    LET BP.NODE = BEST.PATH (XMTR, RCVR, 1)
    'ADD.DESTINATION'
    LET DESTINATION(MESSAGE) = RCVR
    LET TRANS.NUMBER(MESSAGE) = NEW.MSG.TOTAL
    LET PACK.NUMBER(MESSAGE) = I

```



```

"
LET NEXT.STOP(MESSAGE) = BP.NODE

"
IF PRNT >= 1
  SKIP 1 OUTPUT LINE
  PRINT 1 LINE WITH NEW.MSG.TOTAL, 1, XMTR, BP.NODE, FG, RCVR
  AND TIME.V AS FOLLOWS
  ***/** INITIATED FROM *** THRU *** (F/G = ***) TO *** AT ****.***** SEC
  REGARDLESS

"
IF LINK TO BP NEIGHBOR IS IDLE; SEND OUT PACKET

"
IF LINK.MONITOR(XMTR, BP.NODE, 1) = ICLE
  FILE MESSAGE IN LINK.FLAG(XMTR)
  LET LINK.ENTRY.TIME(MESSAGE) = TIME.V
  SCHEDULE A PACKET.ARRIVES GIVEN MESSAGE IN PKT.XMN.TIME UNITS
  LET LINK.MONITOR(XMTR, BP.NODE, 1) = BUSY
  LET LINK.TIMER(1, XMTR, BP.NODE, 1) = TIME.V
  LET RELEASE.TIME(MESSAGE) = TIME.V

"
IF PRNT >= 1
  SKIP 1 OUTPUT LINE
  PRINT 2 LINES WITH LINK.MONITOR(XMTR, BP.NODE, 2) AS FOLLOWS
  FIRST PACKET OF MESSAGE DID NOT WAIT IN OUTGOING PACKET QUEUE
  OUTGOING PACKET QUEUE IS *******
  REGARDLESS

"
IF PRNT >= 5
  SKIP 1 OUTPUT LINE
  PRINT 1 LINE WITH XMTR, BP.NODE, TRANS.NUMBER(MESSAGE),
  PACK.NUMBER(MESSAGE) AND TIME.V AS FOLLOWS
  LINK ***/ *** BUSY TRANSMITTING PACKET ****/** AT ****.***** SEC
  REGARDLESS

"
ELSE
  IF LINK IS BUSY, STORE PKT AT END OF THE OUTGOING PACKET QUEUE
  FOR THAT LINK

  LET QUEUE.ENTRY.TIME(MESSAGE) = TIME.V
  FILE MESSAGE IN PACKET.OUT.QUEUE(XMTR)
  LET LINK.MONITOR(XMTR, BP.NODE, 2) =
  LINK.MONITOR(XMTR, BP.NODE, 2) + 1
  IF LINK.MONITOR(XMTR, BP.NODE, 2) > LINK.MONITOR(XMTR, BP.NODE, 3)
    LET LINK.MONITOR(XMTR, BP.NODE, 3) = LINK.MONITOR(XMTR, BP.NODE, 2)
  REGARDLESS

"
IF PRNT >= 1
  SKIP 1 OUTPUT LINE

```



```

PRINT 2 LINES WITH NEW.MSG.TOTAL, I, XMTR, TIME.V, XMTR AND
LINK.MCNITR( XMTR, BP.NCDE, 2 ) AS FOLLOWS
****/** ENTERS OUTGOING PACKET QUEUE AT NODE *** AT ***** SEC.
OUTGOING PACKET QUEUE AT NODE *** IS *****
REGARDLESS

.. IF LINK QUEUE CHANGES, CREATE A "PACK" (A PACKAGE OF INFORMATION)
.. WHICH CONTAINS THE NEW QUEUE SIZE AND THE TIME IT WAS CHANGED
.. FOR THE LATER CALCULATION OF CV

CREATE A PACK
LET NUMBER(PACK) = LINK.MONITOR (XMTR,BP.NODE,2)
LET ENTRY.TIME(PACK) = TIME.V
LET PAC.NEIGHBOR(PACK) = BP.NODE
FILE PACK IN TIME.QUEUE(XMTR)
REGARDLESS

.. LOOP
.. RESCHEDULE NEXT TRAFFIC SESSION UP TO MAX SET BY TRAFFIC.LIMIT
..
IF NEW.MSG.TOTAL <= TRAF.LIMIT
  SCHEDULE A NEW.PACKET.MESSAGE GIVEN PACKET IN
  EXPONENTIAL.F(MSG.GENERATION.INTERVAL, 1) UNITS
ELSE
  SKIP 1 OUTPUT LINE
PRINT 2 LINES WITH TIME.V AS FOLLOWS
TRAFFIC GENERATION FOR THIS RUN = TRAFFIC LIMIT
SIMULATION TIME = *****
REGARDLESS

RETURN
END **CF NEW.PACKET.MESSAGE

.. THIS ROUTINE PROCESSES PKTS AS THEY ARRIVE IN A NODE
..
EVENT PACKET.ARRIVES GIVEN ID.NUMBER
DEFINE MSG.NR, THIS.NCDE AND PAST.NCDE AS VARIABLES
DEFINE OCCURANCE AS VARIABLE
LET MSG.NR = ID.NUMBER
LET THIS.NODE = NEXT.STOP(MSG.NR)
LET PAST.NODE = RELAYER(MSG.NR)
..
REMOVE MSG.NR FROM LNK.FLAG(PAST.NODE)
LET LINK.ENTRY.TIME(MSG.NR) = 0.0
..
.. CALCULATE TOTAL TIME LINK IS BUSY

```





```

..
LET LINK.TIMER( 1, PAST.NODE, THIS.NCDE, 2) = TIME.V
LET LINK.TIMER( 1, PAST.NODE, THIS.NCDE, 3) = +
LET LINK.TIMER( 1, PAST.NODE, THIS.NCDE, 3) +
LET LINK.TIMER( 1, PAST.NODE, THIS.NCDE, 2) -
LET LINK.TIMER( 1, PAST.NODE, THIS.NCDE, 1)

..
IF PRNT >= 1
  SKIP 1 OUTPUT LINE
  PRINT 1 LINE WITH TRANS.NUMBER(MSG.NR), PACK.NUMBER(MSG.NR),
  RELAYER(MSG.NR), NEXT.STCP(MSG.NR), TIME.V AS FOLLOWS
  ***/** ARRIVES FROM *** INTC *** AT ***.***** SEC.
  REGARDLESS
..
..
.. IF THE PKT HAS REACHED ITS DESTINATION, GO TO A PROCESSING ROUTINE
..
..
IF NEXT.STCP(MSG.NR) = DESTINATION(MSG.NR)
..
LET TRANSIT.TIME = TRANSIT.TIME + TIME.V - ORIG.TIME(MSG.NR)
LET DEST.COUNT = DEST.COUNT + 1
..
.. SCHEDULE A COMPLETED TRIP GIVEN MSG.NR NEXT
..
IF PRNT >= 1
  PRINT 1 LINE AS FOLLOWS
  AND STOPS
  REGARDLESS
..
.. IF PKT IS TO CONTINUE, ADDRESS IT TO THE NEXT BP NEIGHBOR BASED
.. ON THE NODE, GROUP OR FAMILY ID OF THE DESTINATION AS APPROPRIATE.
..
ELSE
..
.. COUNT NUMBER OF PACKETS RELAYED BY THIS.NODE
..
LET PKTS.RELAYED(THIS.NODE) = PKTS.RELAYED(THIS.NODE) + 1
LET RELAYER(MSG.NR) = THIS.NODE
LET FM.GP(MSG.NR) = 0
LET FG = 0
IF FAMILY(THIS.NODE) NE FAMILY(DESTINATION(MSG.NR))
  LET FG = FAMILY(DESTINATION(MSG.NR))
  LET BP.CBJ = FG
  LET FM.GP(MSG.NR) = FG
  GO ASGN.NEXT.STOP
ELSE
IF GROUP(THIS.NCDE) NE GROUP(DESTINATION(MSG.NR))
  LET FG = GROUP(DESTINATION(MSG.NR))
  LET BP.CBJ = FG

```



```

LET FM.GP (MSG.NR) = FG
GO ASGN.NEXT.STOP
ELSE
  LET BP.CBJ = DESTINATION (MSG.NR)
  *ASGN.NEXT.STOP
  LET NEXT.STOP(MSG.NR) = BEST.PATH (THIS.NODE, BP.OBJ, 1)
  LET NODES.HOPPED(MSG.NR) = NODES.HOPPED(MSG.NR) + 1
  ..
  .. SCHEDULE A PROCESSING COMPLETION TIME WHEN THE PKT WILL BE READY
  .. FOR RETRANSMISSION. QUEUE.ENTRY.TIME STARTS BEFORE THE MESSAGE
  .. IS PROCESSED IN ORDER TO ALLOW THE PROCESSING TIME FOR PACKETS
  .. WHICH ARE NOT IN QUEUE AND NOT DELIVERED AT THE END OF THE
  .. SIMULATION TO BE COUNTED AS PART OF THE TIME THE PACKET SPENT
  .. IN THE NETWORK.
  ..
  LET QUEUE.ENTRY.TIME(MSG.NR) = TIME.V
  SCHEDULE A CON.PACKET.MESSAGE GIVEN MSG.NR IN PROCESSING.TIME UNITS
  REGARDLESS
  ..
  .. GO TO THE QUEUING UPDATE QUEUE OF THE NODE WHICH RELAYED THE ABOVE
  .. PACKET. IF THE UPDATE QUEUE IS EMPTY, CHECK THAT NODE'S
  .. PACKET QUEUE TO SEE IF ADDITIONAL PACKETS ARE WAITING FOR
  .. RELAY OR DELIVERY TO THIS NODE AND SCHEDULE THE ARRIVAL OF
  .. THE NEXT PACKET AT THIS NODE. OTHERWISE, REMOVE THE
  .. WAITING UPDATE FROM THE QUEUE AND SCHEDULE ITS ARRIVAL
  .. AT THIS NODE
  ..
  FOR EACH MESSAGE IN UPDATE.CUT QUEUE(PAST.NODE)
  WITH NEXT.STOP(MESSAGE) = THIS.NODE
  FIND THE FIRST CASE
  IF NCNE
  GO CHECK.PACKET.OUT.QUEUE
  ELSE
  REMOVE MESSAGE FROM UPDATE.OUT.QUEUE(PAST.NODE)
  SCHEDULE AN UPDATE.ARRIVES GIVEN MESSAGE IN U.XMN.TIME UNITS
  LET LINK.MONITOR(PAST.NODE, THIS.NODE, 4) = 4) - 1
  LINK.MONITOR(PAST.NODE, THIS.NODE, 4) = 1
  LET LINK.TIMER( 2, PAST.NODE, THIS.NODE, 1) = TIME.V
  LET LINK.MONITOR( 2, PAST.NODE, THIS.NODE, 1) = BUSY
  ..
  IF PRINT >= 4
  SKIP 1 OUTPUT LINE
  PRINT 3 LINES WITH PAST.NODE, THIS.NODE, TIME.V, PAST.NODE AND
  LINK.MONITOR( PAST.NODE, THIS.NODE, 4) AS FOLLOWS
  UPDATE RELEASED FROM OUTGOING UPDATE QUEUE AT NODE ***
  AT ****.***SEC.
  OUTGICNG UPDATE QUEUE AT NODE *** IS ***
  REGARDLESS

```



```

.. IF PRNT >= 5
   SKIP 1 OUTPUT LINE
   PRINT 1 LINE WITH PAST.NODE, THIS.NODE, TIME.V AS FOLLOWS
   LINK ** / *** BUSY WITH UPDATE AT ****.***** SEC.
   REGARDLESS
..
.. GO NO.PACKET.XMT
..
.. CHECK.PACKET.OUT.QUEUE
..
.. GO TO THE OUTGOING PACKET QUEUE OF THE NODE WHICH RELAYED
.. THE ABOVE PACKET. IF EMPTY, DEFINE THE LINK AS IDLE; IF NOT,
.. PLACE THE NEXT PACKET ON THE LINK AND ADJUST THE QUEUE
.. INFORMATION BY CREATING A NEW "PACK"
..
FOR EACH MESSAGE IN PACKET.OUT.QUEUE(PAST.NODE)
  WITH NEXT.STOP(MESSAGE) = THIS.NODE
  FIND THE FIRST CASE
  IF NONE
    LET LINK.MONITOR( PAST.NODE, THIS.NODE, 1 ) = IDLE
  ..
  IF PRNT >= 5
    SKIP 1 OUTPUT LINE
    PRINT 1 LINE WITH PAST.NODE, THIS.NODE AND TIME.V AS FOLLOWS
    LINK ** / *** IDLE AT ****.***** SEC.
    REGARDLESS
  ..
  ELSE
    REMOVE MESSAGE FROM PACKET.OUT.QUEUE(PAST.NODE)
    LET TOT.QUEUE.TIME(MESSAGE) = TOT.QUEUE.TIME(MESSAGE) + TIME.V
    - QUEUE.ENTRY.TIME(MESSAGE)
    LET QUEUE.ENTRY.TIME(MESSAGE) = 0.0
    FILE MESSAGE IN LINK.FLAG(RELAY(MESSAGE))
    LET LINK.ENTRY.TIME(MESSAGE) = TIME.V
    LET LINK.MONITOR( PAST.NODE, THIS.NODE, 2 ) =
    LINK.MONITOR( PAST.NODE, THIS.NODE, 2 ) - 1
    CREATE A PACK
    LET NUMBER(PACK) = LINK.MONITOR ( PAST.NODE, THIS.NODE, 2 )
    LET ENTRY.TIME(PACK) = TIME.V
    LET PAC.NEIGHBOR(PACK) = THIS.NODE
    FILE PACK IN TIME.QUEUE(PAST.NODE)
    IF NODES.HOPPED(MESSAGE) = 0
      LET RELEASE.TIME (MESSAGE) = TIME.V
    REGARDLESS
    LET LINK.TIMER( 1, PAST.NODE, THIS.NODE, 1 ) = TIME.V
  ..
  SCHEDULE THE ARRIVAL OF THE PKT JUST RELEASED FROM THE QUEUE.

```





```

..
.. SCHEDULE A PACKET.ARRIVES GIVEN MESSAGE IN PKT.XMN.TIME UNITS
..
IF PRNT >= 1
  SKIP 1 OUTPUT LINE
  PRINT 4 LINES WITH TRANS.NUMBER(MESSAGE), PACK.NUMBER(MESSAGE),
  RELAYER(MESSAGE), TIME.V, NEXT.STOP(MESSAGE),
  DESTINATION(MESSAGE), FM.GP(MESSAGE), RELAYER(MESSAGE) AND
  LINK.MONITOR( PAST.NODE, THIS.NODE, 2 ) AS FOLLOWS
  RELEASED FROM OUTGOING PACKET QUEUE AT NODE ***
  AT ***.***.***.*** SEC
  PACKET ENROUTE TO NODE *** FOR DESTINATION *** ( F/G = *** )
  OUTGOING PACKET QUEUE AT NODE *** IS *****
  REGARDLESS
..
.. REGARDLESS
.. NO PACKET.XMT.
.. RETURN
.. END .. OF PACKET.ARRIVES
..
.. THIS ROUTINE CONTINUES THE PACKET ON IT BEST PATH AFTER PROCESSING
.. IF THE LINK IS IDLE, OR PLACES IT IN A QUEUE.
..
.. EVENT CON.PACKET.MESSAGE GIVEN IDENT.MESSAGE.NUMBER
..
.. DEFINE MSG.NR AND THIS.NODE AS VARIABLES
.. LET MSG.NR = IDENT.MESSAGE.NUMBER
.. LET THIS.NODE = RELAYER (MSG.NR)
..
.. IF LINK IS AVAILABLE, SEND OUT PKT. LIST LINK AS BUSY.
..
.. IF LINK.MONITOR ( THIS.NODE, NEXT.STOP(MSG.NR), 1 ) = IDLE
  LET TOT.QUEUE.TIME(MSG.NR) = TOT.QUEUE.TIME(MSG.NR) + TIME.V
  - QUEUE.ENTRY.TIME(MSG.NR)
  LET QUEUE.ENTRY.TIME(MSG.NR) = 0.0
  FILE MSG.NR IN LNK.FLAG(THIS.NODE)
  LET LNK.ENTRY.TIME(MSG.NR) = TIME.V
  SCHEDULE A PACKET.ARRIVES GIVEN MSG.NR IN PKT.XMN.TIME UNITS
  LET LNK.TIMER( 1, THIS.NODE, NEXT.STOP(MSG.NR), 1 ) = TIME.V
..
IF PRNT >= 1
  SKIP 1 OUTPUT LINE
  PRINT 3 LINES WITH TRANS.NUMBER(MSG.NR), PACK.NUMBER(MSG.NR),
  RELAYER(MSG.NR), NEXT.STOP(MSG.NR), DESTINATION(MSG.NR),
  FM.GP(MSG.NR), TIME.V, RELAYER(MSG.NR) AND LINK.MONITOR(RELAYER
  (MSG.NR), NEXT.STOP(MSG.NR), 2 ) AS FOLLOWS
  ***** RELAYED *** THRU *** FOR *** (F/G = *** ) AT *****.***** SEC

```





```

        PACKET DID NOT WAIT IN OUTGOING PACKET QUEUE
        OUTGCING PACKET QUEUE FROM NCDE *** IS *****
    REGARDLESS
..
.. LET LINK.MONITOR( THIS.NODE, NEXT.STOP(MSG.NR), 1) = BUSY
..
    IF PRNT >= 5
        SKIP 1 OUTPUT LINE
        PRINT 1 LINE WITH RELAYER(MSG.NR), NEXT.STOP(MSG.NR),
            TRANS.NUMBER(MSG.NR), PACK.NUMBER(MSG.NR) AND
            TIME.V AS FOLLOWS
            LINK ** / *** BUSY TRANSMITTING PACKET *** / ** AT ***.***** SEC
    REGARDLESS
..
    ELSE
..
.. IF LINK WAS BUSY, PLACE PKT IN QUEUE AND CREATE A PACK WITH NEW
.. QUEUE INFORMATION.
..
    FILE MSG.NR IN PACKET.OUT.QUEUE(THIS.NCDE)
    LET LINK.MONITOR (THIS.NODE, NEXT.STOP(MSG.NR), 2) =
    LINK.MONITOR (THIS.NODE, NEXT.STOP(MSG.NR), 2) + 1
    IF LINK.MCNITOR (THIS.NODE, NEXT.STOP(MSG.NR), 2) >
    LINK.MCNITOR (THIS.NODE, NEXT.STOP(MSG.NR), 3)
    LET LINK.MONITOR (THIS.NODE, NEXT.STOP(MSG.NR), 3) =
    LINK.MONITOR (THIS.NODE, NEXT.STOP(MSG.NR), 2)
    LINK.MCNITOR (THIS.NODE, NEXT.STOP(MSG.NR), 2)
    REGARDLESS
    CREATE A PACK
    LET NUMBER(PACK) = LINK.MONITOR (THIS.NODE, NEXT.STOP(MSG.NR), 2)
    LET ENTRY.TIME(PACK) = TIME.V
    LET PAC.NEIGHBOR(PACK) = NEXT.STOP(MSG.NR)
    FILE PACK IN TIME.QUEUE (THIS.NODE)
..
    IF PRNT >= 1
        SKIP 1 OUTPUT LINE
        PRINT 2 LINES WITH TRANS.NUMBER(MSG.NR), PACK.NUMBER(MSG.NR),
            THIS.NODE, NEXT.STOP(MSG.NR), TIME.V, THIS.NODE AND
            LINK.MCNITOR (THIS.NODE, NEXT.STOP(MSG.NR), 2) AS FOLLOWS
            *** ** / ** ENTERS OUTGOING PACKET QUEUE IN *** FOR *** AT ***.***** SEC.
    REGARDLESS
..
    REGARDLESS
    RETURN
END ** CF CON.PACKET.MESSAGE
..
.. THIS ROUTINE COLLECTS STATISTICAL DATA WHEN A PKT REACHES ITS

```



```

.. DESTINATION.
..
EVENT COMPLETED. TRIP GIVEN MES.NUM
DEFINE DEL.TIME AS A REAL VARIABLE
LET MESSAGE = MES.NUM
LET CNTR = NODES.HOPPED(MESSAGE) + 1
..
IF LONGEST.PATH < CNTR
  LET LONGEST.PATH = CNTR
REGARDLESS
..
.. PRINT ALERT IF NODES HOPPED >= TOTAL NODES IN NETWORK.
..
IF SPECIFY.OUTPUT = 0
..
  IF (CNTR >= N.NODE AND MSG.HLT = 0)
    PRINT 1 LINE AS FOLLOWS
    PROBLEM -- MORE HOPS THAN NODES
    LET MSG.HLT = 1
    REGARDLESS
  .. REGARDLESS
  ..
  .. INCREMENT COUNTER FOR TOTAL NODES HOPPED FOR THIS PKT AND SUM NET
  .. TIME FOR GIVEN NUMBER OF HOPS.
  ..
  LET HOP.COUNT (CNTR, PACKET) = HOP.COUNT (CNTR, PACKET) + 1
  LET DEL.TIME = TIME.V - RELEASE.TIME (MESSAGE)
  LET CLOCK.DATA (CNTR, 1) = CLOCK.DATA (CNTR, 1) + DEL.TIME
  ..
  .. NOTE IF THIS TRANSIT TIME IS A NEW MAX FOR THIS NUMBER OF HOPS.
  ..
  IF DEL.TIME > CLOCK.DATA (CNTR, 2)
    LET CLOCK.DATA (CNTR, 2) = DEL.TIME
  REGARDLESS
  ..
  .. INCREMENT TRACER ARRAY WHICH KEEPS THE NUMBER OF PKTS GENERATED
  .. AND THE NUMBER REACHING THEIR DESTINATION.
  ..
  LET TRACER (TRANS.NUMBER(MESSAGE), 2) = TRACER(TRANS.NUMBER(MESSAGE), 2) + 1
  ..
  .. DESTROY MESSAGE CALLED MES.NUM
  .. RETURN
  .. END .. OF COMPLETED.TRIP
  ..
  .. THIS ROUTINE IDENTIFIES A SET OF THE BUSIEST LINKS

```



```

.. OVER THE FIRST HALF OF THE SIMULATION SO THAT
.. THE QUEUE SIZES OF THESE LINKS CAN BE SAMPLED
.. DURING THE SECOND HALF OF THE TEST. CRITERIA FOR
.. SELECTION OF THE BUSIEST LINKS IS BASED ON THE
.. NUMBER OF UPDATES (FOR 'UP.SMP.SET(*,*)') AND
.. NUMBER OF PACKETS (FOR 'PKT.SMP.SET(*,*)') PASSED
.. OVER THE LINK.
EVENT QU.SAMPLER
.. IF SPECIFY.OUTPUT = 0
..
.. SKIP 1 OUTPUT LINE
.. PRINT 1 LINE AS FOLLOWS
..-----MID POINT-----
.. SKIP 1 OUTPUT LINE
..
.. REGARDLESS
..
.. ID THE LARGEST OUTGOING PACKET AND UPDATE QUEUE SIZES
.. DURING THE FIRST HALF OF THE SIMULATION.
FOR F = 1 TC N.NODE, DO
FOR T = 1 TO N.NODE, DO
IF P.Q.MAX < LINK.MONITOR (F,T,3)
LET P.Q.MAX = LINK.MONITOR (F,T,3)
REGARDLESS
IF U.Q.MAX < LINK.MONITOR (F,T,5)
LET U.Q.MAX = LINK.MONITOR (F,T,5)
REGARDLESS
LOOP
.. SMP.LINKS IS AN INPUT VARIABLE LISTING THE NUMBER OF LINKS TO BE
.. SAMPLED FOR QUEUE SIZE.
LET I = 1
..
.. FILL.PKT.SMP.SET,
FOR F = 1 TC N.NODE, DO
FOR T = 1 TO N.NODE, DO
IF LINK.MONITOR (F,T,3) = P.Q.MAX
LET PKT.SMP.SET(I,1) = F
LET PKT.SMP.SET(I,2) = T
IF I = SMP.LINKS
GO NCW.FILL.UP.SMP.SET
ELSE
LET I = I+1

```



```

GO HCP.NEW.P.Q.MAX
ELSE
IF NEW.P.Q.MAX < LINK.MCNITOR(F,T,3) AND LINK.MONITOR(F,T,3)
< P.Q.MAX
LET NEW.P.Q.MAX = LINK.MONITOR(F,T,3)
REGARDLESS
'HOP.NEW.P.Q.MAX'
LCCP
LOOP
LET P.Q.MAX = NEW.P.Q.MAX
GO FILL.PKT.SMP.SET
,,
'NOW.FILL.UP.SMP.SET'
LET I = 1
,,
'FILL.UP.SMP.SET'
FOR F = 1 TO N.NODE, DC
FOR T = 1 TO N.NODE, DC
IF LINK.MCNITOR(F,T,5) = U.Q.MAX
LET UP.SMP.SET(I,1) = F
LET UP.SMP.SET(I,2) = T
IF I = SMP.LINKS
GO BEGIN.SAMPLING
ELSE
LET I = I + 1
GO HCP.NEW.U.Q.MAX
ELSE
IF NEW.U.Q.MAX < LINK.MONITOR(F,T,5) AND LINK.MONITOR(F,T,5)
< U.Q.MAX
LET NEW.U.Q.MAX = LINK.MONITOR(F,T,5)
REGARDLESS
'HOP.NEW.U.Q.MAX'
LOCP
LOOP
LET U.Q.MAX = NEW.U.Q.MAX
GO FILL.UP.SMP.SET
,,
SCHEDULE FIRST SAMPLE OF ALL LINKS IN SMP.SET
,,
'BEGIN.SAMPLING'
LET TI.MER = TIME.LIMIT/(2.*REAL.F(NO.OF.SAMPLES))
SCHEDULE A SAMPLE IN (EXPONENTIAL.F(TI.MER, 8)) UNITS
RETURN
END ** OF QU.SAMPLER
,,
,,
THIS ROUTINE SAMPLES THE LINKS IDENTIFIED IN QU.SAMPLER WITH AN
EXPONENTIAL SAMPLING RATE.

```





```

''
EVENT SAMPLE
''
'' COUNT ACTUAL SAMPLES TAKEN.
''
LET SMP.CNTR = SMP.CNTR + 1
''
'' INCREMENT COUNTER BASED ON QUEUE SIZE.
''
FOR I = 1 TC SMP.LINKS, DO
  LET PKT.QU.DISTR( LINK.MCNTR( PKT.SMP.SET(I,1),
    PKT.SMP.SET(I,2), 2 ) + 1 ) = PKT.QU.DISTR( LINK.MONITOR
    (PKT.SMP.SET(I,1), PKT.SMP.SET(I,2), 2) + 1 ) + 1
  ''
  LET UP.QU.DISTR( LINK.MONITOR( UP.SMP.SET(I,1),
    UP.SMP.SET(I,2), 4 ) + 1 ) = UP.QU.DISTR( LINK.MONITOR
    (UP.SMP.SET(I,1), UP.SMP.SET(I,2), 4) + 1 ) + 1
  LOOP
''
'' SCHEDULE THE NEXT SAMPLE.
''
'' TI.MER IS DEFINED IN QU.SAMPLER
''
SCHEDULE A SAMPLE IN (EXPONENTIAL.F(TI.MER,8)) UNITS
RETURN
END '' OF SAMPLE
''
''-----
/*GC.SIMU06 DD VOL=SER=MVS004,UNIT=3350,DISP=SHR,DSN=SI611.JEN,
/*GC.SIMU08 DD DISP=SHR,DSN=MSS.SI611.WZSN57
/**DCB=(RECFM=FB,LRECL=133,BLKSIZE=4123)
/*GC.SYSIN DD *

```



## APPENDIX D

### LISTING OF ARRAYS USED IN THE SIMULATION PROGRAMS

Arrays common to all programs:

#### 1 - dimensional arrays

FAM.OF.GRP (no.of nodes + groups + 25)  
1st -- program ID of the i-th group

HISTOGRAM (10)  
1st -- no. of links with utilization  
factor =  $i/10$

PKT.QU.DISTR (1000)  
1st -- number of times packet queue size = i

UP.QU.DISTR (1000)  
1st -- number of times update queue size = i

#### 2 - dimensional arrays

CLOCK.DATA (10 \* no.of nodes, 2)  
1st -- number of hops = N  
2nd -- 1 = net time for all packets hopping  
N nodes  
2 = highest individual trip time for  
a N hop packet



HOP.COUNT (10 \* no.of nodes, 2)  
 1st -- number of hops = N  
 2nd -- 1 = not used  
       2 = no.of packets hopping N nodes

LINK.ABLE (no.of links, 2)  
 1st -- link number  
 2nd -- 1 = first end node  
       2 = second end node

PKT.SMP.SET (selected links to be sampled, 2)  
 1st -- sample link ID number  
 2nd -- 1 = 'from' node ID  
       2 = 'to' node ID

TRACER (estimate of the maximum number of  
           messages, 2)  
 1st -- message number  
 2nd -- 1 = number of packets in the message  
       2 = number of packets of the message  
           which reach their destination

UP.SMP.SET (selected links to be sampled, 2)  
 1st -- sample link ID number  
 2nd -- 1 = 'from' node ID  
       2 = 'to' node ID



### 3 - dimensional arrays

BEST.PATH (no. of nodes + groups, no. of nodes  
                  + groups, 4)  
1st -- 'from' node, group or family ID  
2nd -- 'to' node, group or family ID  
3rd -- 1 = current best path neighbor  
          2 = channel value through the current  
              best path neighbor  
          3 = best path neighbor to be adopted  
              during next update cycle  
          4 = channel value to best path  
              neighbor which will be adopted  
              during next update cycle

LINK.MONITOR (2 \* no. of links, 2 \* no. of links, 6)  
1st -- 'from' node ID  
2nd -- 'to' node ID  
3rd -- 1 = link status (idle/busy)  
          2 = current packet queue of link  
          3 = max packet queue thus far  
          4 = current update queue of link  
          5 = max update queue thus far  
          6 = no. of packets in queue at the  
              simulation halt

NEIGHBOR.LIST (no. of nodes, max links per node, 3)  
1st -- i-th node ID  
2nd -- ID number of link  
3rd -- 1 = neighbor node ID  
          2 = link status (idle/busy)  
          3 = channel value from node to neighbor





#### 4 - dimensional array

```
LINK.TIMER (2, 2 * no. of links, 2 * no. of links,  
3)  
1st -- 1 = packet  
       2 = update  
2nd -- sending node ID  
3rd -- receiving node ID  
4th -- 1 = start time for busy link  
       2 = stop time for busy link  
       3 = cumulative time link is busy  
       4 = cumulative time link busy up to  
           simulation half
```

Additional arrays for Djiksta algorithm:

#### 2 - dimensional arrays

```
ADDRESS.LIST (no. of nodes, no. of nodes)  
1st -- sending node ID  
2nd -- destination node ID
```

```
ADD.RESS.LIST (no. of nodes, no. of nodes)  
1st -- sending node ID  
2nd -- destination node ID
```

```
DJIKSTRA.MATRIX (no. of nodes, no. of nodes)  
1st -- sending node ID  
2nd -- destination node ID
```

```
PATH.AVAIL (no. of nodes, no. of nodes)  
1st -- sending node ID  
2nd -- destination node ID
```



# APPENDIX E

## SAMPLE INPUT AND OUTPUT DATA

Input data set:

1				- node.factor
5				- n.node
1.	1.	1	1	- transmit.percent( )
1.	1.	1	1	- receive.percent( )
1.	1.	1	1	- group( )
1.	1.	1	1	- family( )
0.1				- ip.date.period
0.0001				- processing.time
0.05				- pkt.xmn.time
30.				- time.limit
0.5				- window ( for channel value )
00.	00.			- in.group - in.family
0				- print
5	500			- smp.links - no.of.samples
0				- links
4				- max.links.per.node
1	2			- node no. - node no. (defines link ends)
1	3			
1	4			
1	5			
2	3			
2	4			
2	5			
3	4			
3	5			
4	5			



Output data set:

#####

# NEW SIMULATION

#####

MAX.FKTS.PER.MSG = 10.00  
PKTS.PER.SEC.AVE = 150.00

-- UTILIZATION FACTOR --				PKTS IN	PKTS IN	WAIT TIME	
LINK	PACKET	UPDATE	TOTAL	QUEUE AT HALF	QUEUE AT END	FOR PKTS	
1							
1/	2	.616658	.044519	.661177	0	2	1.791269
2/	1	.566655	.046663	.613318	10	0	1.437693
1/	3	.606655	.047601	.654255	6	0	1.724311
3/	1	.543331	.045553	.588924	1	14	1.295773
1/	4	.605999	.045454	.655453	4	0	1.741389
4/	1	.565994	.045723	.615717	0	0	1.455954
1/	5	.545987	.045556	.595583	0	0	1.333076
5/	1	.645981	.046126	.696107	0	0	2.107410
2/	3	.606654	.045332	.651986	11	0	1.714382
3/	2	.623334	.047988	.671322	0	3	1.865066
2/	4	.656654	.045329	.701983	3	14	2.172235
4/	2	.579990	.047192	.627182	4	10	1.526965
2/	5	.543325	.046662	.589987	12	0	1.298548
5/	2	.593328	.047728	.641056	0	0	1.623242
3/	4	.579999	.047586	.627585	0	16	1.528421
4/	3	.639987	.049457	.689444	0	7	2.027481
3/	5	.546652	.047190	.593843	14	5	1.318838
5/	3	.666648	.050806	.717454	6	0	2.323752
4/	5	.579988	.047987	.627975	15	5	1.529767
5/	4	.625984	.047727	.687710	12	4	2.017254

AVE.P.FLOW = .598490  
AVE.U.FLOW = .046913  
AVE.NETWORK.FLOW = .645403  
GEN.COUNT = 4421  
DEST.COUNT = 4314  
TRANSIT.TIME = 3051.942139  
STRANDED.WAIT = 49.100677  
T.IN.LINK = .401688  
Q.IN.LINK = 10.718658  
CHECK.DELAY = .703950  
AVE.DELAY.PER.PKT = .225555  
RATIO.STRANDED = .024803  
PKTS IN QUEUE AT HALF = 98  
PKTS IN QUEUE AT END = 93

INTERVAL	NUMBER OF LINKS
0. - .10	0
.10 - .20	0
.20 - .30	0
.30 - .40	0
.40 - .50	0
.50 - .60	4
.60 - .70	14
.70 - .80	2
.80 - .90	0
.90 - 1.00	0

SIMULATION STEPS



## APPENDIX F

### GRAPHICAL RESULTS

DELAY : HERITSCH ALGORITHM ; SYNCHRONOUS  
NODES - 5, LINKS - 10

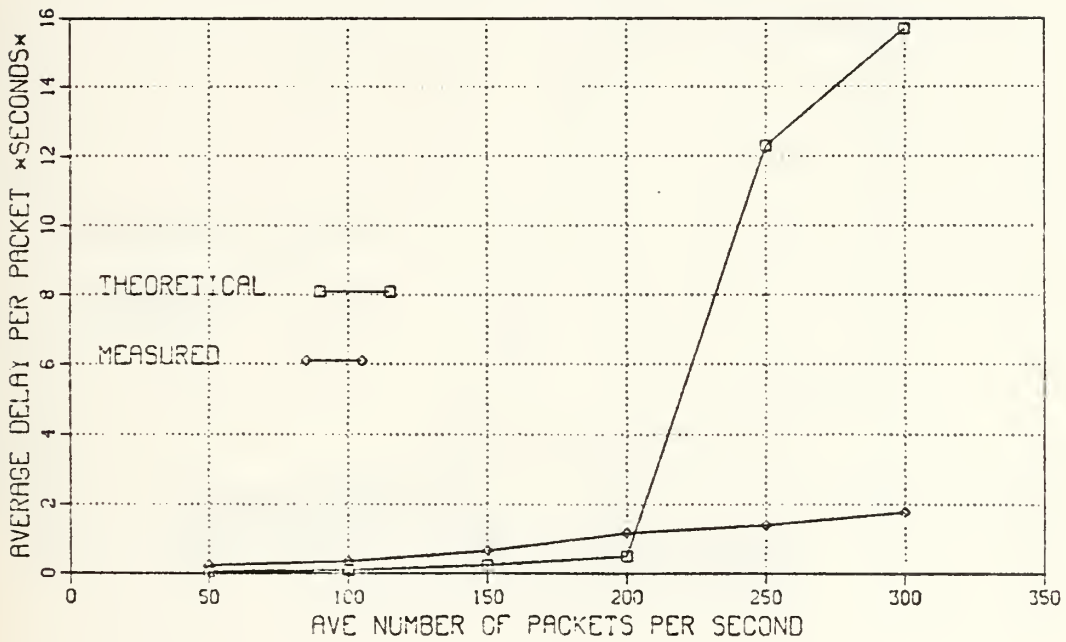


Fig. F.1. Delay: Heritsch (synch), Network 5/10





DELAY : HERITSCH ALGORITHM ; SYNCHRONOUS  
NODES - 10, LINKS - 20

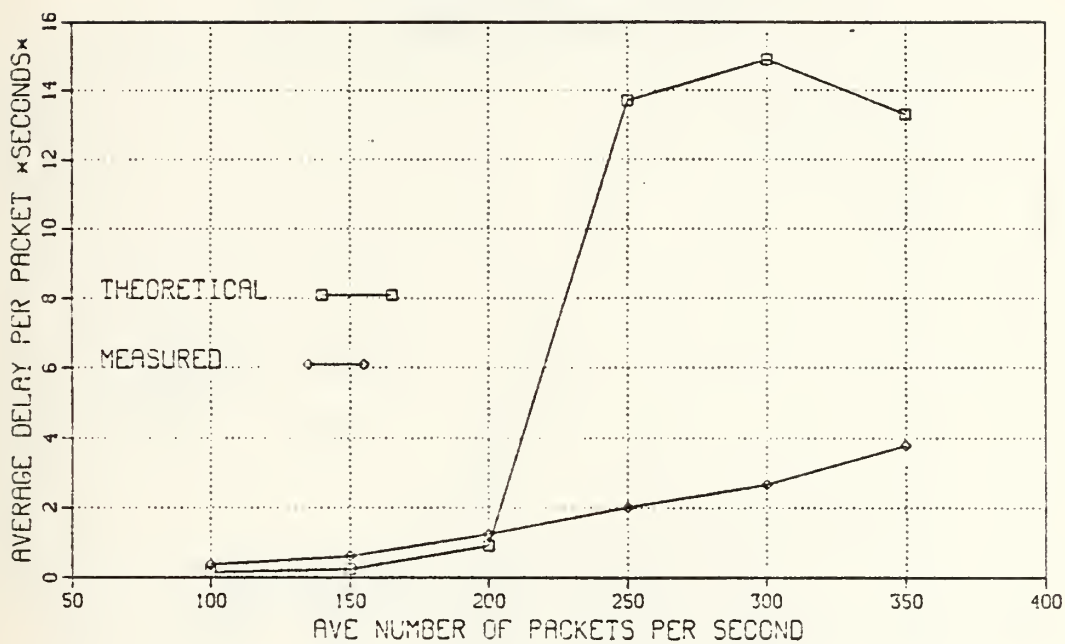


Fig. F.2. Delay: Heritsch (synch), Network 10/20



DELAY : HERITSCH ALGORITHM ; SYNCHRONOUS  
 NODES - 15, LINKS - 30

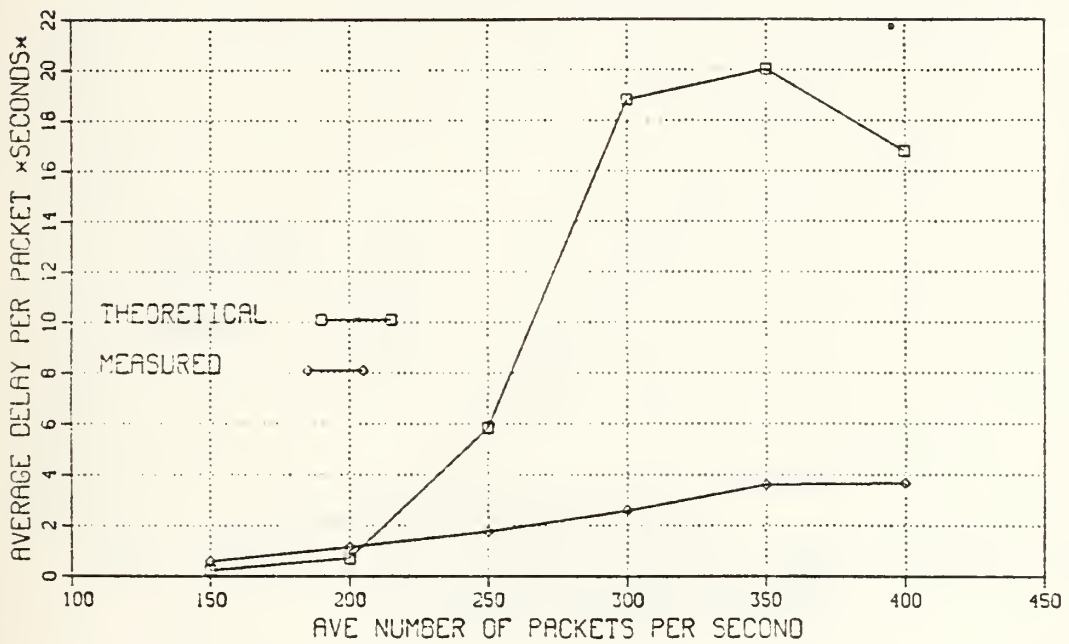


Fig. F.3. Delay: Heritsch (synch), Network 15/30



DELAY : HERITSCH ALGORITHM ; SYNCHRONOUS  
NODES - 20, LINKS - 40

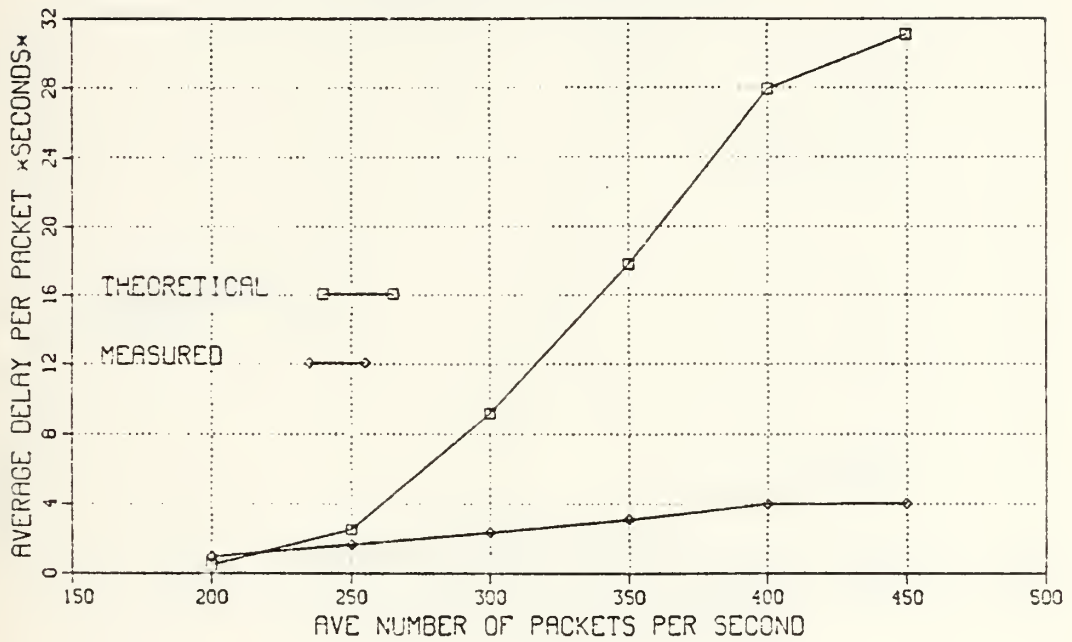


Fig. F.4. Delay: Heritsch (synch), Network 20/40



DELAY : HERITSCH ALGORITHM ; ASYNCHRONOUS  
NODES - 10, LINKS - 20

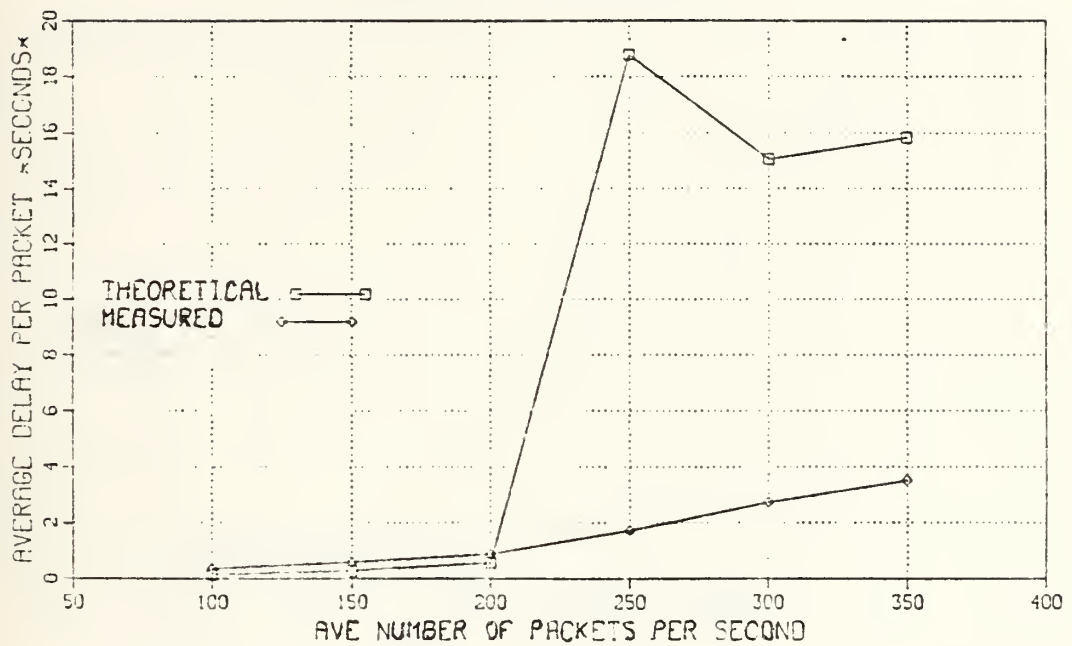


Fig. F.5. Delay: Heritsch (synch), Network 10/20 (2 groups)





DELAY : HERITSCH ALGORITHM ; ASYNCHRONOUS  
 NODES - 15, LINKS - 30

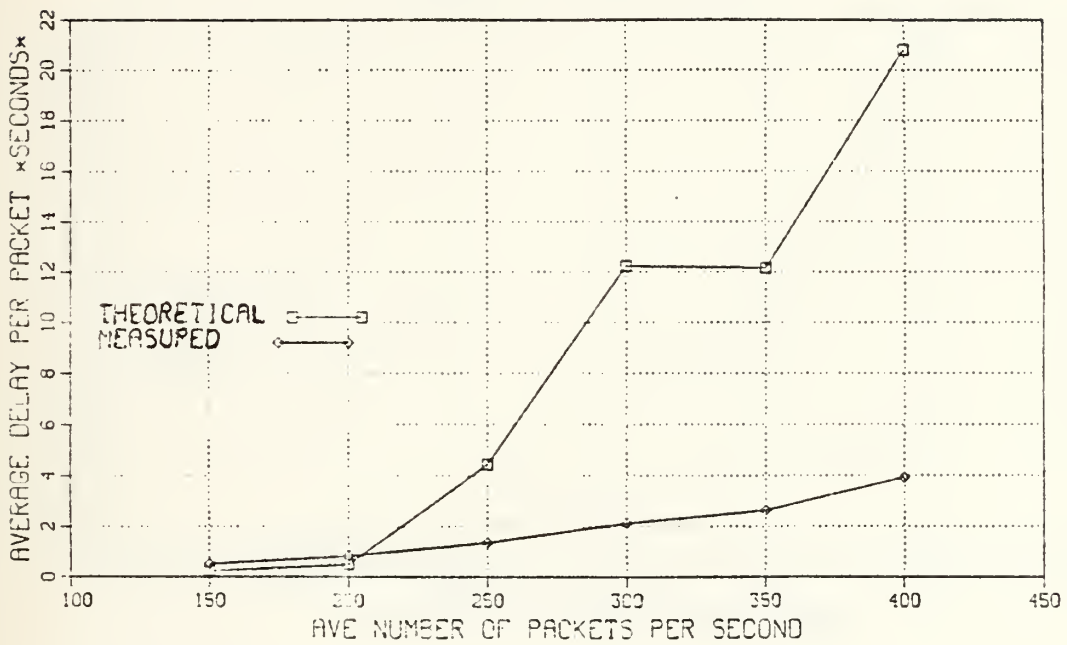


Fig. F.6. Delay: Heritsch (synch), Network 15/30 (3 groups)



DELAY : HERITSCH ALGORITHM ; SYNCH : GROUP  
 NODES - 10, LINKS - 20

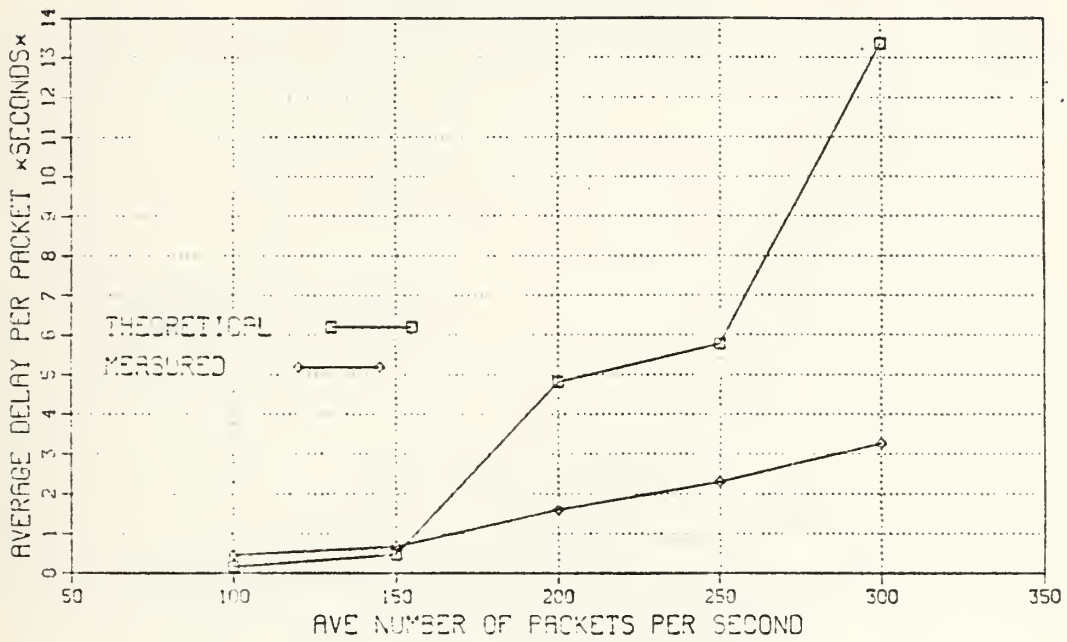


Fig. P.7. Delay: Heritsch (asynch), Network 10/20



DELAY : HERITSCH ALGORITHM ; SYNCH : GROUP  
 NODES - 15, LINKS - 30

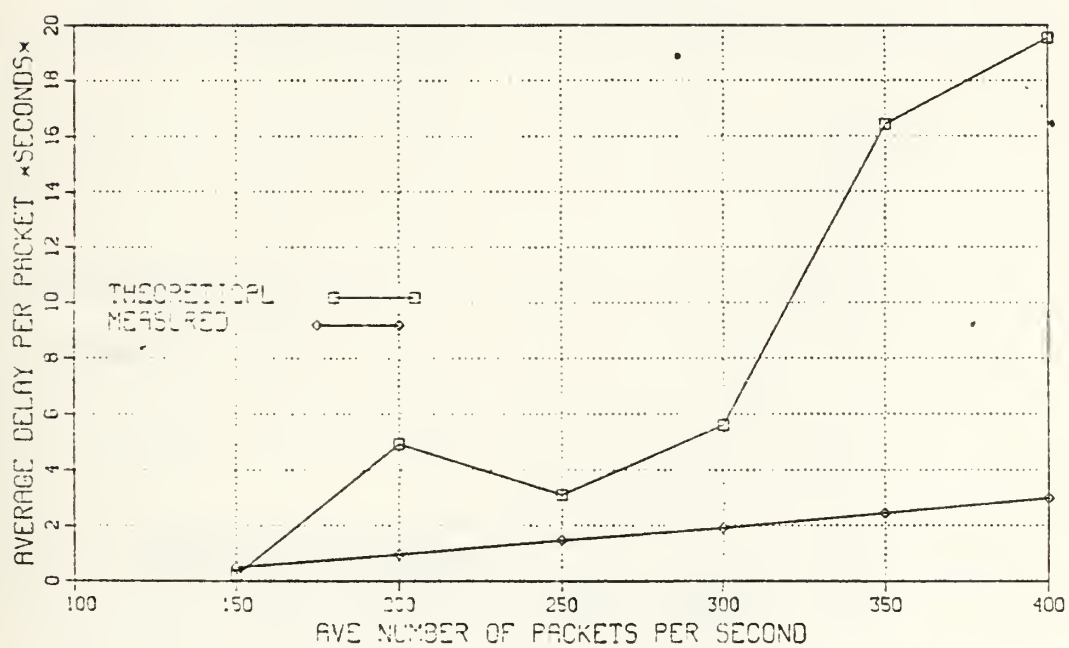


Fig. F.8. Delay: Heritsch (asynch), Network 15/30



DELAY : DIJKSTRA ALGORITHM ; SYNCHRONOUS  
NODES - 5, LINKS - 10

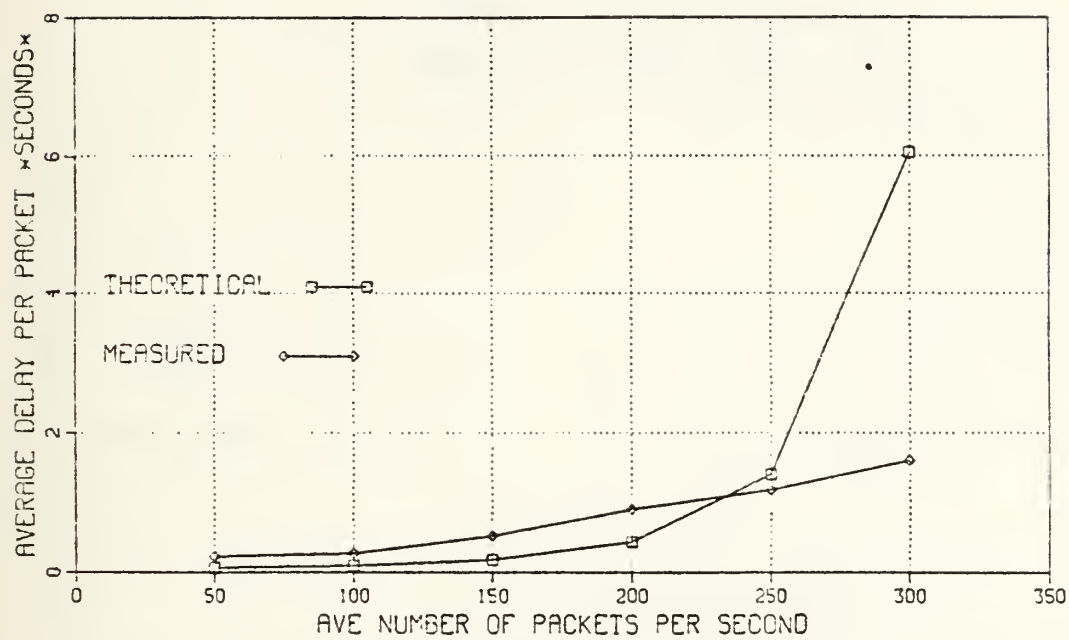


Fig. F.9. Delay: Dijkstra, Network 5/10





DELAY : DIJKSTRA ALGORITHM ; SYNCHRONOUS  
NODES - 10, LINKS - 20

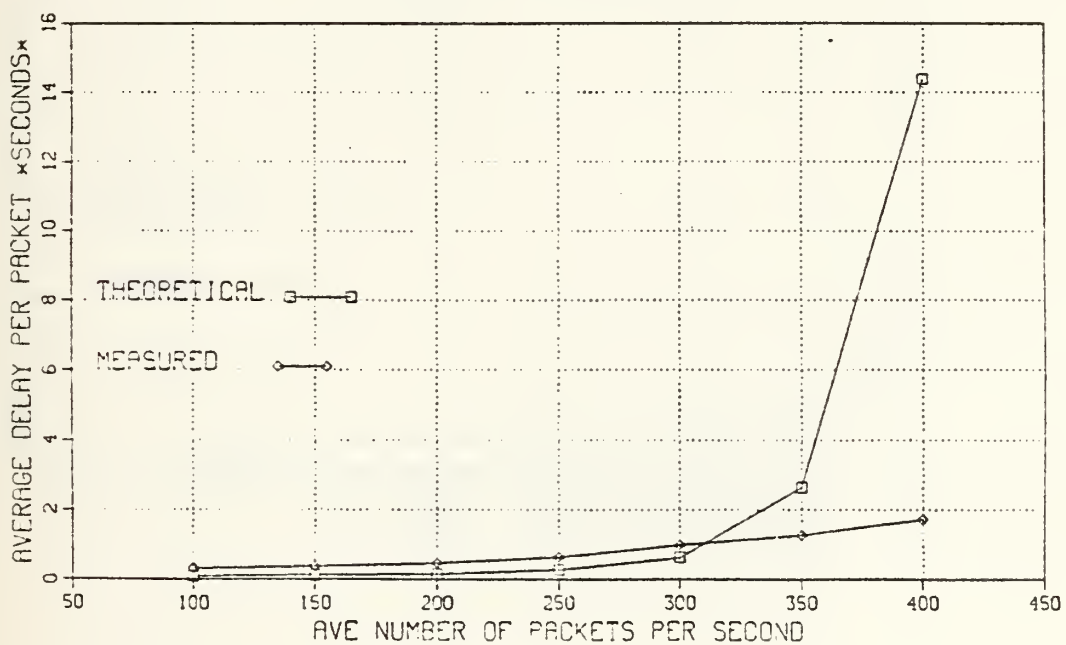


Fig. F.10. Delay: Dijkstra, Network 10/20



DELAY : DIJKSTRA ALGORITHM ; SYNCHRONOUS  
NODES - 15, LINKS - 30

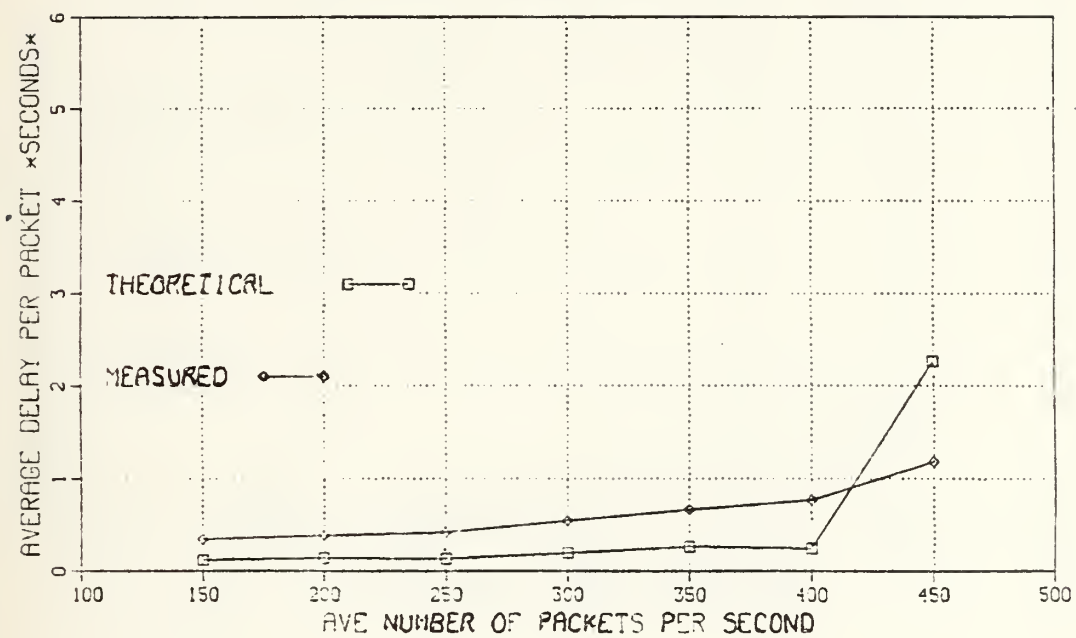


Fig. F.11. Delay: Dijkstra, Network 15/30



DELAY : DIJKSTRA ALGORITHM ; SYNCHRONOUS  
NODES - 20, LINKS - 40

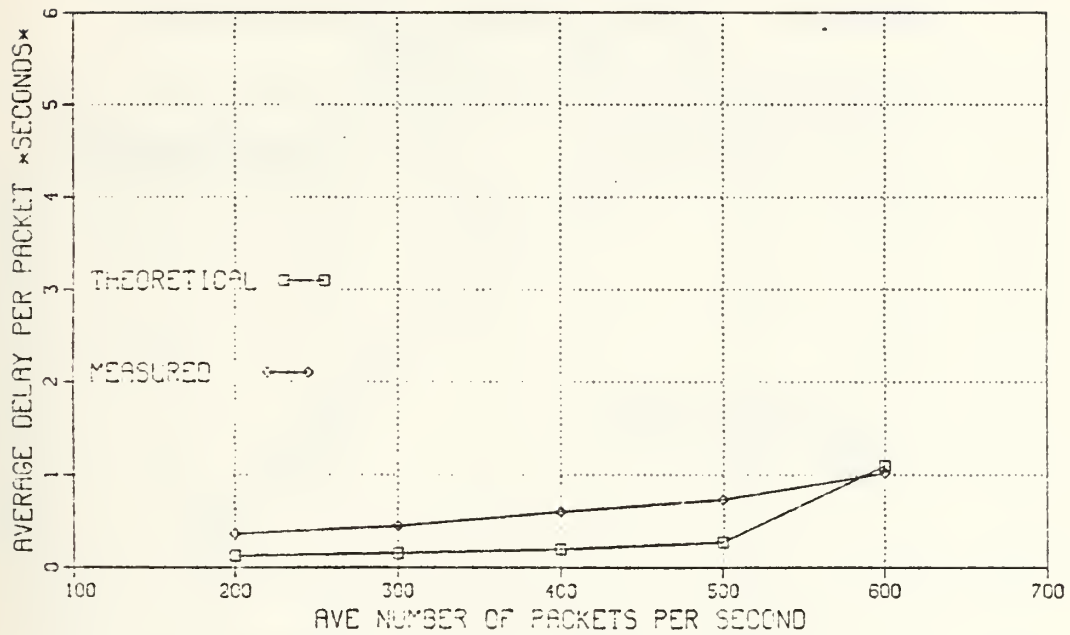


Fig. F.12. Delay: Dijkstra, Network 20/40



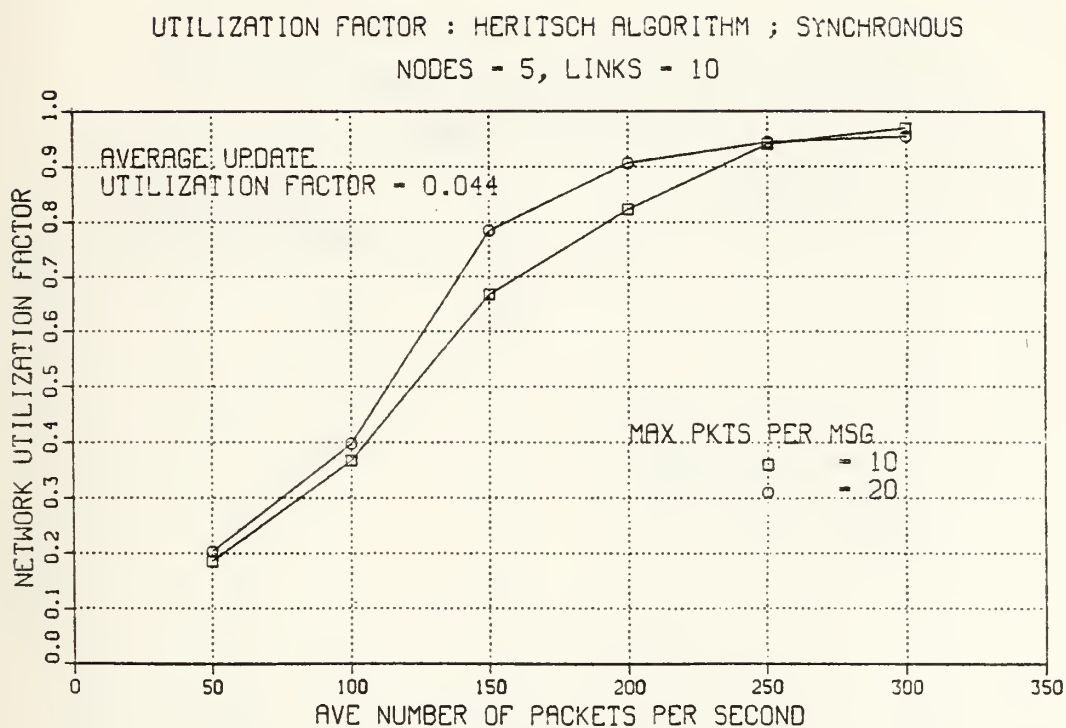


Figure F.13. Utilization Factor: Heritsch (synch), Network 5/10





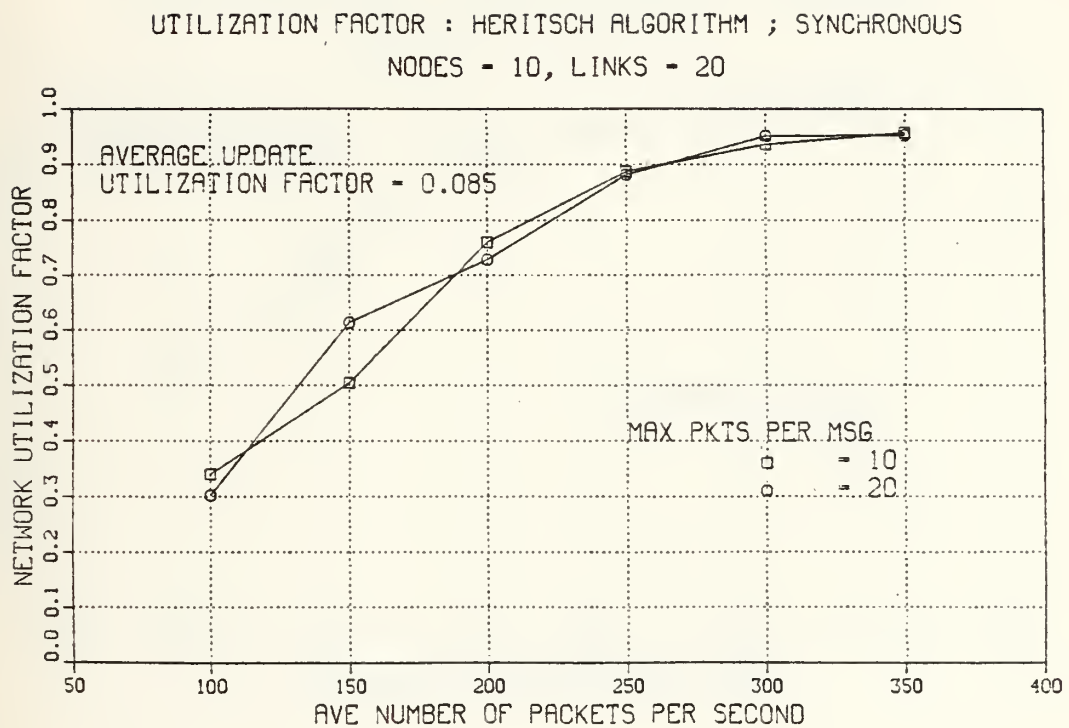


Figure F.14. Utilization Factor: Heritsch (synch), Network 10/20



UTILIZATION FACTOR : HERITSCH ALGORITHM ; SYNCHRONOUS  
 NODES - 15, LINKS - 30

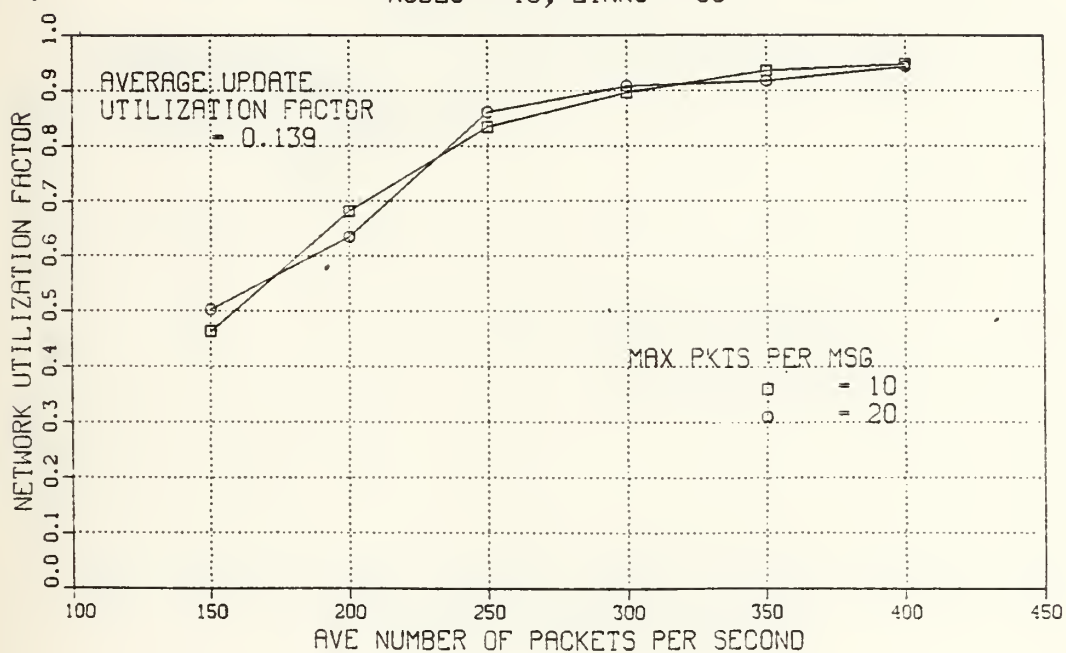


Figure F.15. Utilization Factor: Heritsch (synch), Network 15/30



UTILIZATION FACTOR : HERITSCH ALGORITHM ; SYNCHRONOUS  
NODES - 20, LINKS - 40

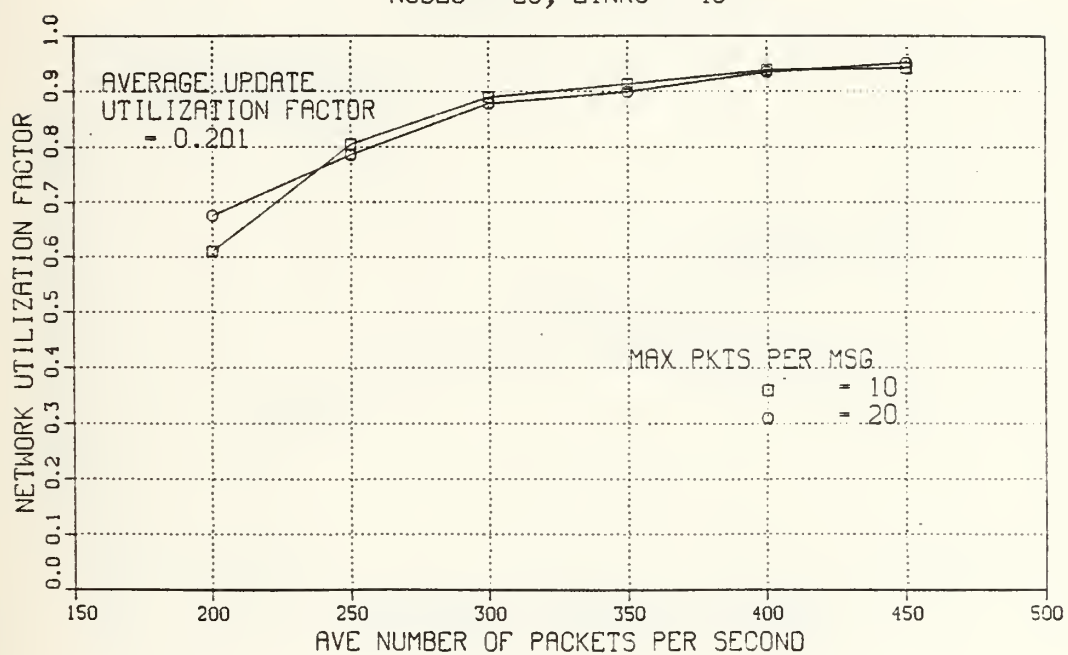


Figure F.16. Utilization Factor: Heritsch (synch), Network 20/40



UTILIZATION FACTOR : HERITSCH ALGORITHM ; SYNCH : GROUPS  
NODES = 10, LINKS = 20

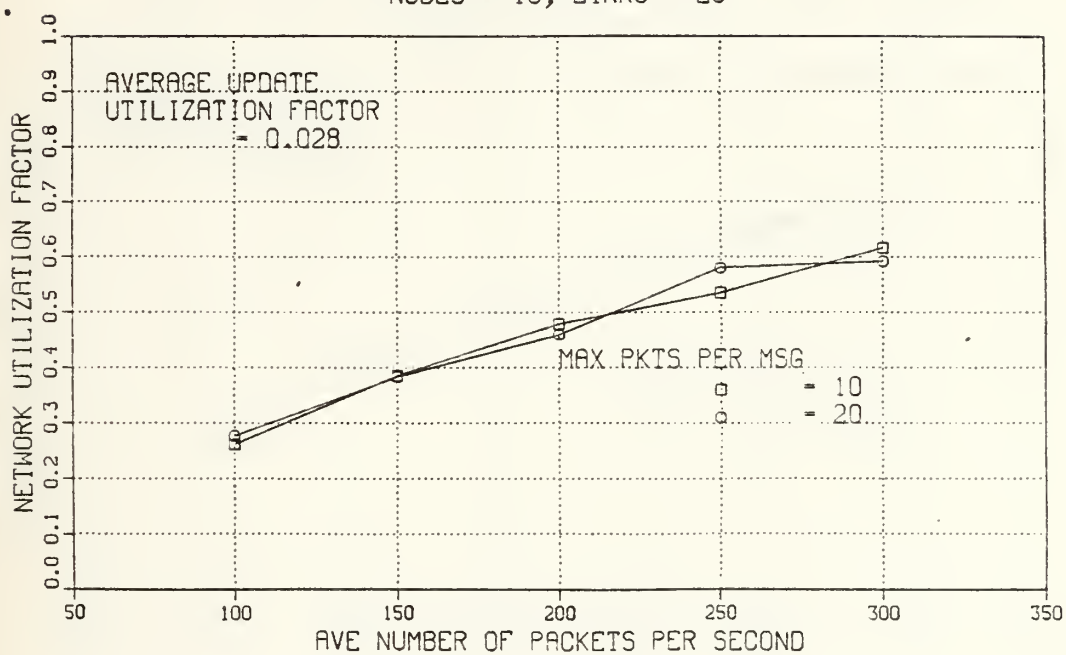


Figure F.17. Utilization Factor: Heritsch (synch), Network 10/20 (2 groups)





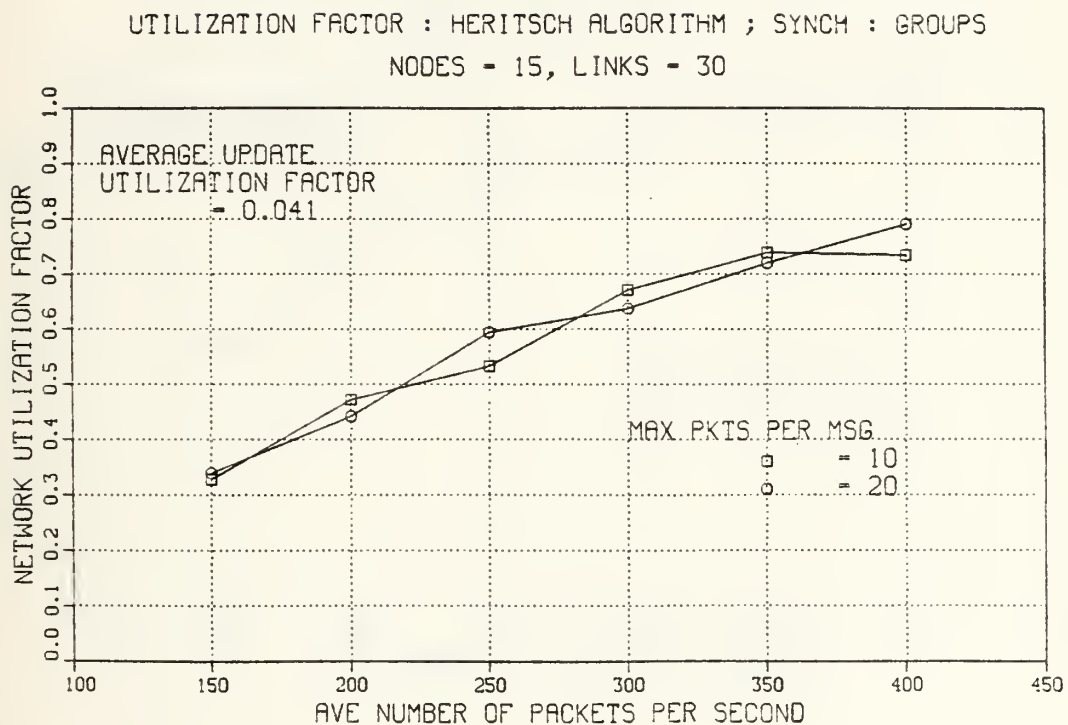


Figure F.F8. Utilization Factor: Heritsch (synch), Network 15/30 (3 groups)



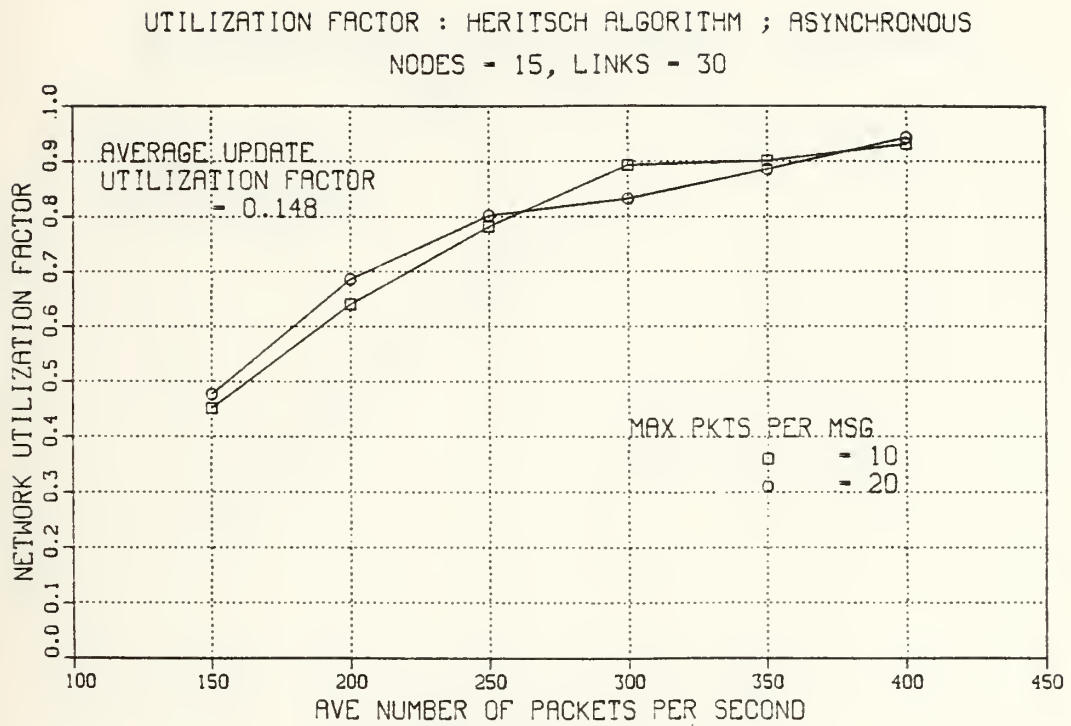


Figure F.19. Utilization Factor: Heritsch (asynch), Network 10/20



UTILIZATION FACTOR : HERITSCH ALGORITHM ; ASYNCHRONOUS  
 NODES - 10, LINKS - 20

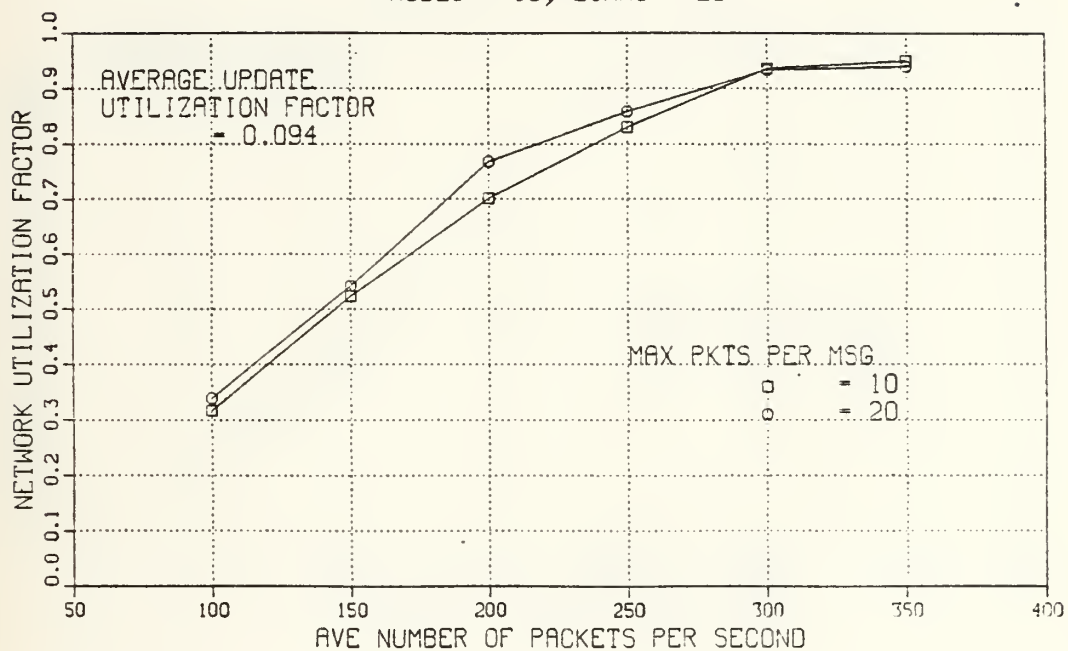


Figure F.20. Utilization Factor: Heritsch (asynch), Network 15/30



UTILIZATION FACTOR : DJIKSTRA ALGORITHM ; SYNCHRONOUS  
 NODES - 5, LINKS - 10

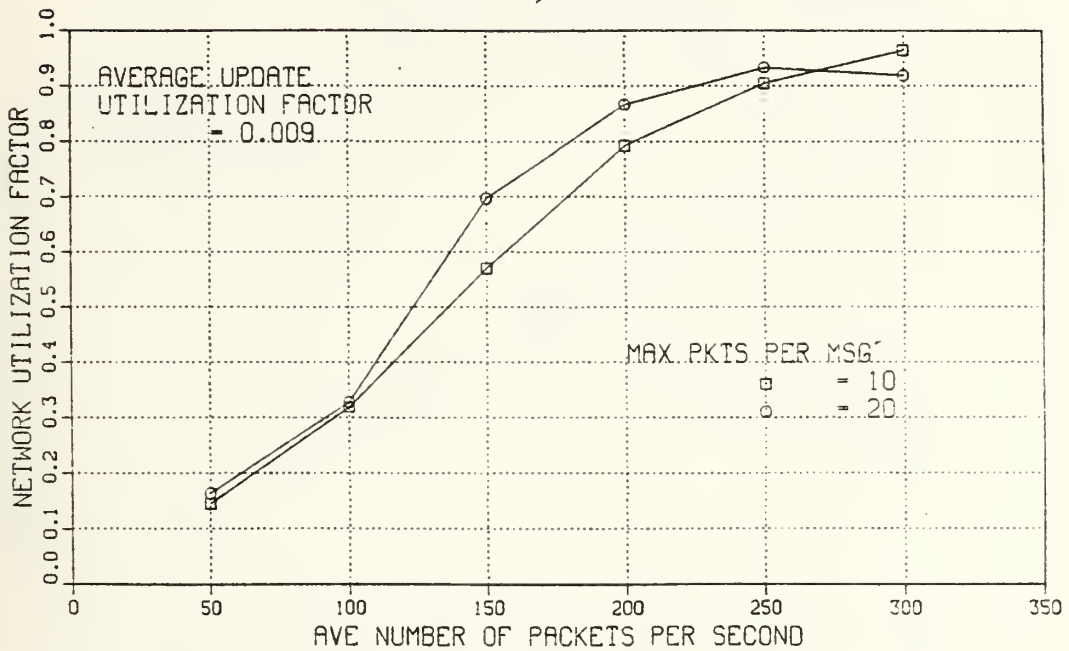


Fig. F.21. Utilization Factor: Dijkstra, Network 5/10





UTILIZATION FACTOR : DIJKSTRA ALGORITHM ; SYNCHRONOUS  
 NODES - 10, LINKS - 20

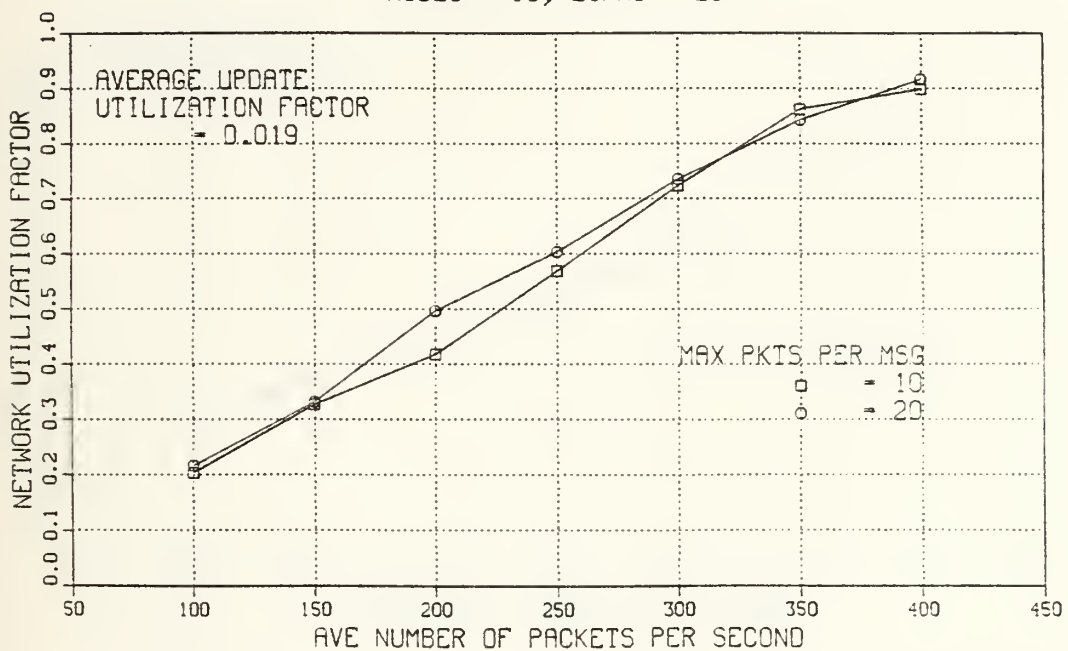


Fig. F.22. Utilization Factor: Dijkstra, Network 10/20



UTILIZATION FACTOR : DIJKSTRA ALGORITHM ; SYNCHRONOUS  
 NODES - 15, LINKS - 30

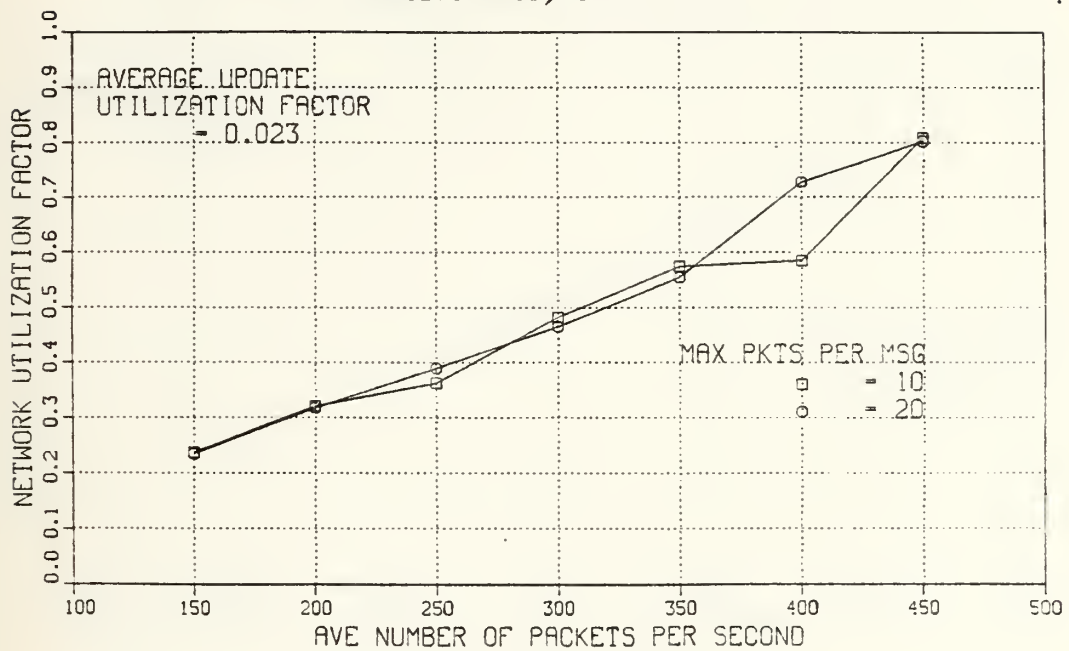


Fig. F.23. Utilization Factor: Dijkstra, Network 15/30



UTILIZATION FACTOR : DIJKSTRA ALGORITHM ; SYNCHRONOUS  
NODES - 20, LINKS - 40

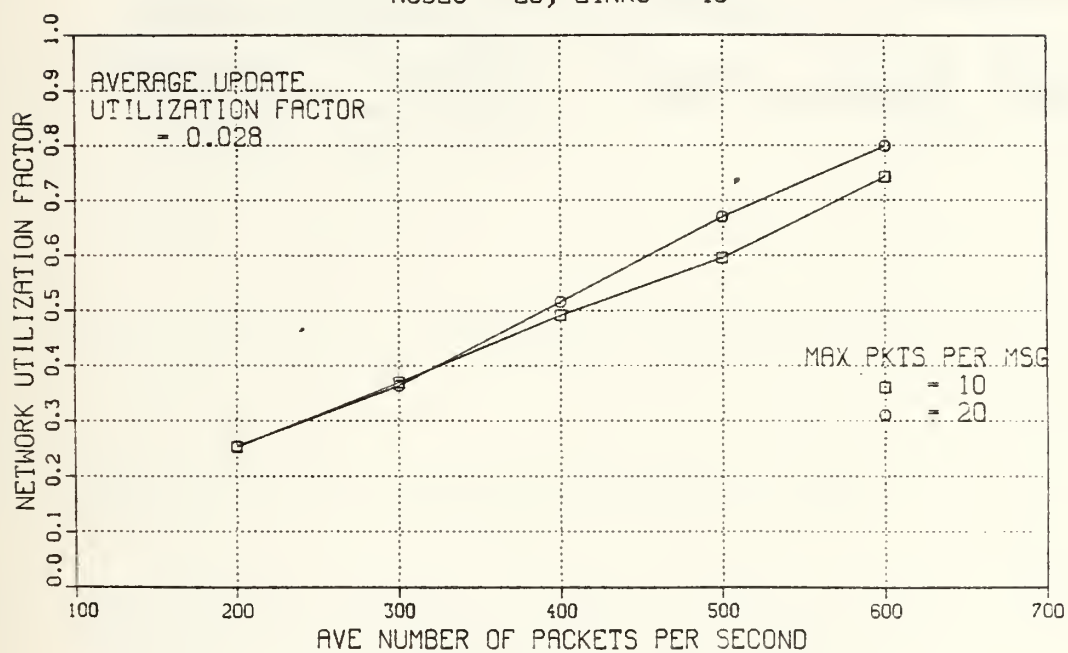


Fig. F.24. Utilization Factor: Dijkstra, Network 20/40



## LIST OF REFERENCES

1. Tanenbaum, Andrew, S., Computer Networks, p.16-21, Prentice Hall Inc., 1981.
2. Heritsch, Robert, A Distributed Routing Protocol for a Packet Radio Network, Master's Thesis, Naval Postgraduate School, Monterey, California, March 1982.
3. Djikstra, E.W., "A Note on Two Problems in Connexion with Graphs" Numerische Mathematik 1, p. 269-271, 1959
4. Kiviat, P.J., Villanueva, R., and Markowitz, H.M., SIMSCRIPT II.5 Programming Language, CACI Inc., 1975.
5. Gross, Donald, and Harris, Carl, M., Fundamentals of Queueing Theory, p. 52 -59, Wiley, 1974.
6. Kleinrock, Leonard, Queueing Systems, Volume 2: Computer Applications, p. 320 - 322, Wiley, 1976.





# INITIAL DISTRIBUTION LIST

	No. Copies
1. Defense Technical Information Center Cameron Station Alexandria, CA 223 14	2
2. Library, Code 0142 Naval Postgraduate School Monterey, CA 93940	2
3. Department Chairman, Code 62 Department of Electrical Engineering Naval Postgraduate School Monterey, CA 93940	1
4. Prof. J. M. Wozencraft, Code 62 Department of Electrical Engineering Naval Postgraduate School Monterey, CA 93940	3
5. C3 Division (Code D102) Development Center Marine Corps Development Education Command Quantico, VA 22134	2
6. Prof. Robert G. Gallager Laboratory for Information and Decision Systems Massachusetts Institute of Technology Boston, Ma 01239	1
7. Dr. Vincent Cerf Information Processing Techniques Office Defense Advanced Research Projects Agency Washington, D.C. 20390	1
8. Dr. Barry M. Leiner Information Processing Techniques Office Defense Advanced Research Projects Agency Washington, D.C. 20390	1
9. Naval Electronics Systems Command Code 03 Washington, D.C. 20390	1
10. Naval Electronics Systems Command Marine Corps Representative, Code PME - 154 Washington, D.C. 20390	1
11. Office of Naval Research Marine Corps Representative, Code 100M Washington, D.C. 20390	1



12. Commander, Naval Ocean System Center 2  
Code 447 (Library)  
San Diego, CA 92152
13. Capt. Kenneth L. Moore, USAF 1  
Code 62 Mz  
Department of Electrical Engineering  
Naval Postgraduate School  
Monterey, CA 93940
14. PM, Test Measurement and Diagnostics Systems 1  
Attn: DRCPM-TMDS (Maj Robert Heritsch, USA)  
Ft. Monmouth, NJ 07703
15. Lcdr Anthony W. Lengerich, USN 3  
Staff, Commander Carrier Group TWO  
FPO New York, NY 09501
16. Lt. George Wasenius, USN 1  
SMC 1162  
Naval Postgraduate School  
Monterey, CA 93940
17. Lt. S. Constandoulakis, HN 1  
Antoniou Paraskeva 5  
Marousi  
Athens, Greece
18. Capt. W.K. Tritschler, USMC 1  
SMC 1162  
Naval Postgraduate School  
Monterey, CA 93940
19. Capt. R. Logan, USMC 1  
SMC 1231  
Naval Postgraduate School  
Monterey, CA 93940







200034

Thesis

L5165 Lengerich

c.1      Investigations into  
the performance of a  
distributed routing  
protocol for packet  
switching networks.



Investigations into the performance of a



3 2768 001 03187 5

DUDLEY KNOX LIBRARY